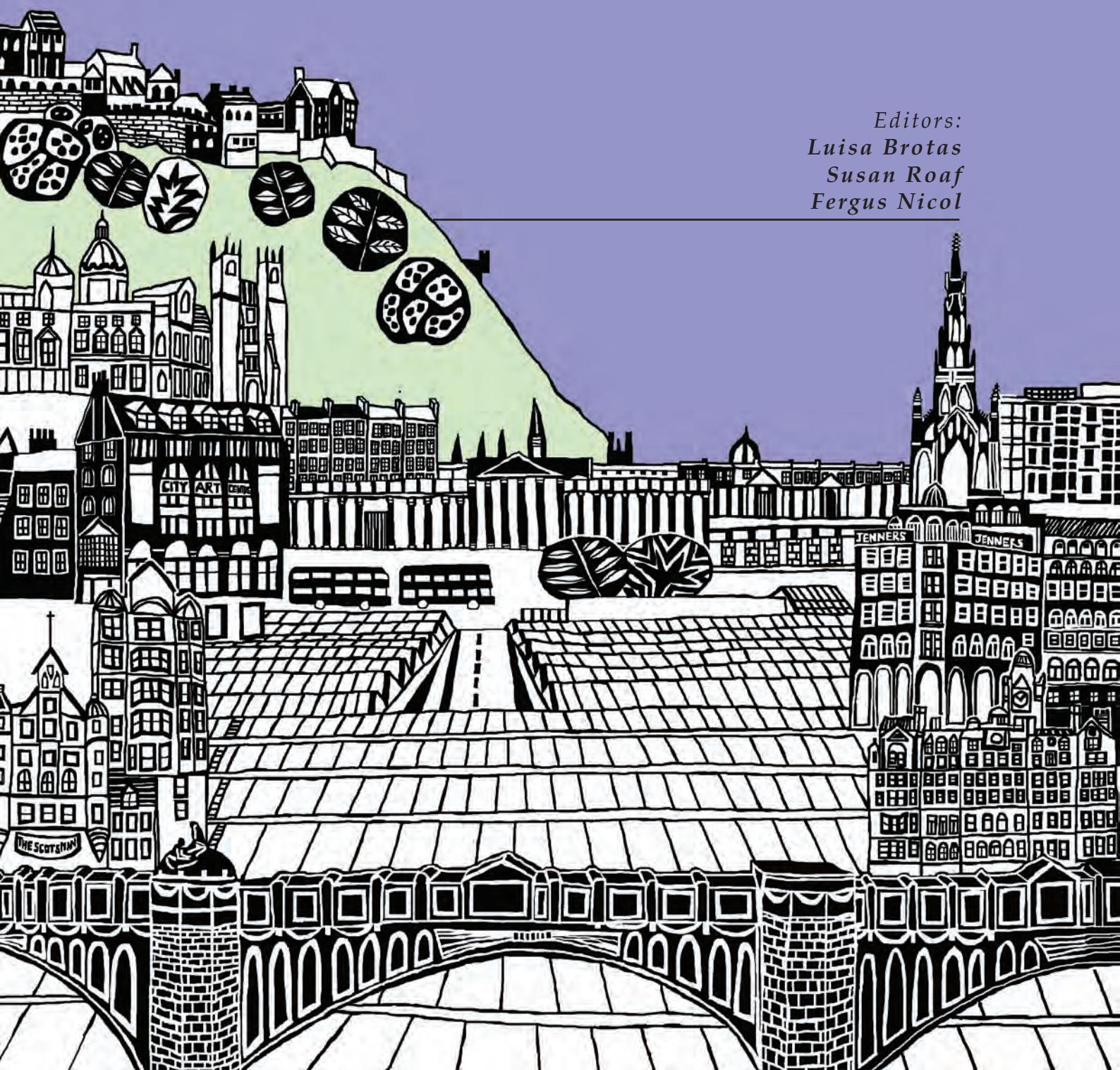


# DESIGN TO THRIVE

## *Proceedings* *Volume I*

PLEA 2017 Conference

Editors:  
Luisa Brotas  
Susan Roaf  
Fergus Nicol



# Design to Thrive - PLEA 2017

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All contributions to the 2017 PLEA Conference included herein were independently peer reviewed as a full paper, prior to publication.

# Introduction to the Proceedings of PLEA 2017

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The question we all too often forget to ask is Why? Why, for instance did we in Edinburgh set out on the PLEA 2017 journey to give ourselves all the very hard work of creating a huge conference in which people from all over the world were invited to discuss and develop ideas of Passive and Low Energy Buildings (PLEA)? Well the answer is that we believe the issue of good building design, embraced for thirty five years by the PLEA movement is simply one of the most important there is in the evolution of a safer world in which people will be able to live comfortable and affordable lives in a rapidly changing world.

The PLEA organisation started in 1982 as a small group of international friends dedicated to the ideal of sharing knowledge on how to design and operate minimal and renewable energy buildings. The development of solar buildings lay at the core of its ethos in those early days and still does. PLEA now has a membership of several thousand professionals, academics and students from over forty countries ([www.plea-arch.org](http://www.plea-arch.org)). Having expected three to five hundred abstracts for the 2017 PLEA conference we were overwhelmed by more than fourteen hundred.

*It is obvious that the time for PLEA thinking has come.*

Where better to share these important ideas than in Edinburgh, the 18th Century capital of the European 'Age of Enlightenment'? It is here we set about creating our Team Scotland to organise the conference, held on the 2nd – 5th July 2017 and including 665 papers published in these Proceedings. The impressive list of people who helped us included: the Scottish schools of architecture and engineering, the City of Edinburgh, the Scottish Government, Historic Environment Scotland, the Royal Incorporation of Architects in Scotland, the Chartered Institution of Building Services Engineers and a host of related professional companies and organisations.

Reflecting the diverse interests of the team involved, the subject matter of the conference is separated in the following proceedings into papers sorted according to the thirty-one Forums in which they were presented at the conference. Readers should first review the contents lists to see which subject areas are of particular interest to them and then browse through the varied papers by selected Forums. Separation of the papers into these various fields enabled authors to present their ideas at the conference to smaller groups with whom they could expertly explore and discuss their own results while learning from other related studies that might lend light to their own thinking.

# Introduction to the Proceedings of PLEA 2017

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In discussions at one of our Forum Leader meetings we decided that in reality many of the larger challenges we face could be distilled down into five different themes:

- Building Better, Safer Places for All (inclusion and resilience)
  - Designing to Thrive in a Changing world (affordability and well-being in good buildings)
  - Learning from, and building on, the Lessons of the Past (evidence based design evolution)
  - Powering our Lives with Sustainable Energy (clear, durable and affordable futures)
  - Empowering Current Generations (Education for change)
- 

These themes run through in the pages of these proceedings, and were accompanied at the conference itself by a fascinating exchange of ideas, interpretations and assumptions and their attendant design solutions.

The conference was also accompanied by a simple Enlightenment message, presented in four flanking banners in the Ballroom of the Assembly Rooms where generations have deliberated since it was first opened at the height of the original Age of Enlightenment two hundred and thirty ago:

Sun – Light – Wind – Natural Energy Buildings

*The Editors:  
Luisa Brotas  
Sue Roaf  
Fergus Nicol*

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*PLEA 2017 Conference*

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- Adapting to Climate Change
- Aesthetics and Design
- Bridging the Performance Gap
- Building Performance Evaluation
- Carbon Accounting
- Comfort and Delight
- Community Energy
- Construction

## **Volume II includes the following forums:**

- Cool Cities and Urban Heat Islands
- Culture and Society
- Digital Design
- Education and Training
- Energy Efficiency
- Future City Visions
- Green Infrastructure
- Health and Air Quality
- Historic Buildings and Refurbishment
- Light

## **Volume III includes the following forums:**

- Low Carbon Design
- Materials
- Overheating
- Passive Climatic Design
- Place Making and Well-being
- Renewables Solar and Hydrogen Buildings
- Resilience Aging and Adapting to Change
- Sound
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- Ventilation
- Water and Waste
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All made this conference possible.

## Editors

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*Luisa Brotas*

Luisa Brotas is an architect (RIBA) with a PhD in Daylighting. She was Course Leader of the MSc Architecture, Energy and Sustainability and co-director of the Low energy architecture Research unit at London Metropolitan University until 2016. Luisa also taught at other Universities and worked in National Research Institutes in both UK and Portugal. She is Vice-Chair of the Daylight Group of CIBSE and Secretary of the Network for Comfort and Energy Use in Buildings. Luisa is currently Director of Submissions for the PLEA 2017 and organiser the International Windsor Conference 2018. Luisa has also been the initiator of six People and Buildings, a conference for Masters Students in sustainable buildings. Research and consultancy include projects related to daylight and thermal analysis, visual and adaptive thermal comfort, energy efficiency in new and retrofit buildings, eco materials and sustainability, natural ventilation and Passivhaus standard. Recent interests also address climate change and overheating in Europe and resilient buildings and cities

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*Fergus Nicol*

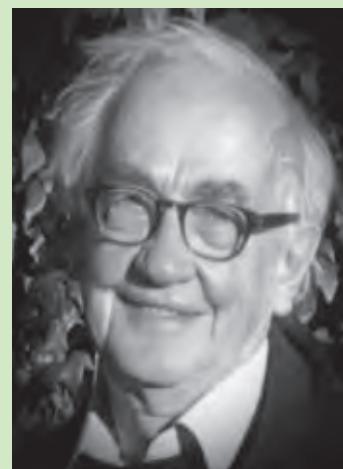
Fergus Nicol is best known for his work in human thermal comfort, principally the 'adaptive' approach and with Professors Michael Humphreys and Susan Roaf is author of the leading book on the subject *Adaptive thermal comfort: principles and practice*, (2012 Routledge). The second volume of this intended trilogy is *Adaptive thermal comfort: foundation and analysis* (2016) is recently published with Humphreys as lead author. He led the EU project Smart Controls and Thermal Comfort (SCATS) which is the basis of European comfort standard EN15251 which he helped draft. Fergus helped develop Masters courses on sustainability at Oxford Brookes and London Metropolitan Universities and supervises a number of PhD students. He has co-authored numerous journal articles and other publications including the comfort chapter in CIBSE Guide A. He was a member of the CIBSE task force on overheating in buildings and is the principal author of CIBSE TM52 *The limits of thermal comfort, avoiding overheating in European buildings* (2013). Fergus convenes the Network for Comfort and Energy use in Buildings and is presently organising their 9th international conference 'Making Comfort relevant' in Windsor, UK in April 2016. He is part-retired but divides his working time between London Metropolitan, Oxford Brookes and Heriot Watt Universities and University College London.



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*Design to Thrive*

## **Building Resilience for Future Climate: An Investigation of Fabric Optimisation to Improve Thermal Comfort in Residential Buildings in Lagos, Nigeria**

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**Abstract:** Nigeria is not left out of the consequences of climate change. In recent time, Lagos experienced one of the most intense heat wave in its history which was a prolonged period of abnormally hot weather with temperature exceeding 32.2°C accompanied by high humidity levels that resulted in the increase in the level of thermal discomfort of occupants within the residential environment. The Lagos future climate is projected to cause more increase in temperature and frequent occurrence of a heat wave. The author investigated the current and the future performance of the residential buildings in respects to the time within and above comfort temperature. This study was developed using Lagos HOMS residential building typology, a low-cost mass housing project by the Lagos state government to reduce the housing deficit. It was selected as it is a repeated mass housing with an expected lifespan of 20 -100 years. This study hopes to improve the thermal performance of the buildings and life of the occupants in changing climate. The current performance of the building presented a high degree of overheating period while the future performance indicated a more severe overheating period. The improvement study showed that the optimisations of the building fabric resulted in slight improvement to the present and 2050 time in comfort period, but in 2080 it presented a significant improvement in the comfort period.

**Keywords:** Climate Change, Thermal Performance, Thermal Comfort, Residential Buildings, Lagos, Nigeria

### **Introduction**

Africa has been identified as one of the most vulnerable continents due to its high exposure and low adaptive ability as reported by fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014). One of the expected consequences of climate change is the increase in occurrences of heat waves and hot weathers in many urban environments (Huth et al., 2000, Beniston et al., 2007). The study by New et al. (2006) shows that the number of cold days and cold nights have decreased and the number of warm days and warm nights have increased between 1961 and 2000 in West Africa and Sahel. It was projected that the Temperatures in Africa are to rise faster than the global average increase during the 21st century (Christensen et al., 2007; Joshi et al., 2011).

Lagos is a coastal city located in the southwestern geopolitical zone of Nigeria. Lagos has been more vulnerable to consequences of climate change in Nigeria, in last few years, the city has experienced several heat waves. The most recent and intense heatwave that hit Lagos was in March 2016 with the temperature reading as high as 36°C with high humidity as recorded by the Nigerian Meteorological Agency (NIMET) (Kazeem, 2016). At all times of

the day during the heat wave period, the room temperature exceeded the normal threshold in many houses making people feel ill at ease (Atuma, 2016). It also made smooth night's rest almost impossible leaving millions of households in restlessness and several heat-related illnesses like heat rash, heat cramp and fatigue. (Dumo & Olajide, 2016).

The use of active cooling system can reduce thermal discomfort during the heat waves, but the erratic power supply in Nigeria coupled with high energy consumption and the cost of maintaining gasoline and diesel power generators make it unaffordable especially for low-income households. Aside from that studies revealed that the use of active cooling system in building is not the ultimate solution and environmentally friendly method as it emitted waste heat to the surrounding environment of the building, which in turn intensify the urban heat island effect (Levermore, et al., 2004, Sailor, 2011, Li & Zhao, 2012).

This paper presents a study of thermal performance of typical Lagos Home Ownership Mortgage Scheme, a low-income mass housing typology, to current and future climates and the application of fabric optimisations to improve indoor thermal comfort in changing climate scenarios.

### **Lagos Home Ownership Mortgage Scheme (Lagos Homs)**

The Lagos HOMS was the selected residential building case study because of its significant representation of residential mass housing that is repeated in different locations in Lagos and is not designed to use the active cooling system as the build costs would be too high to be considered for a low-income earner's scheme. It is expected that newly built housing typical lifespan is 20 – 100 years which makes Lagos HOMS an important case study to investigate the influence of future climate scenario on thermal comfort in residential housing in Lagos.

#### ***Case Study Description***

The selected prototype design comprises of 12 residential apartments of one to three bedroom on four floors. Each floor of the prototype comprises of three apartments as shown in Figure 1. It has a courtyard opened to the stair halls. The bedrooms have two windows which are mainly in the east, west and north façade, while the kitchen windows are opened to the courtyard. It has a butterfly roof covered by long span aluminium roofing sheet which slopes inwards with central concrete roof slab. The roof has 1m eaves at all its sides. Figure 2 shows one of the completed Lagos HOMS. The windows used are casement with 90% effective opening.



Figure 1. Floor plans and completed blocks of Lagos HOMS at Ilupeju Lagos

The building structural frames are made of reinforced concrete. The external and internal walls are made of rendered and painted sandcrete hollow blocks. The roof covering is long-span aluminium roofing sheet while the ceiling and the floor are finished with PVC tiles and Vitrified ceramic tiles respectively.

### **Thermal Simulation and Base Case Study**

The scope of the simulations is based on the indoor air temperature in relation to thermal comfort temperature of the selected simulation spaces. The dynamic model approach was used for this study to understand building performance in different climate scenarios. IES-VE was selected as the simulation software because of its sufficient validity for calculating thermal analysis and humidity in spaces and it could perform accurately in nearly all the analysed hour of thermal simulation.

The third-floor level was chosen as the study floor because it represents the worst case scenario of the building as it is closest to the roof that is fully exposed to solar radiation. The results of the dynamic building simulations were analysed in terms of percentage of hours in thermal comfort. The adopted limits of comfort temperature for Lagos is (23.5°C to 28.5°C) using Szokolay (2008)  $T_n$  equation, thus, any temperature below 23.5°C is considered to be under heated and if it is above 28.5°C is considered as overheating.

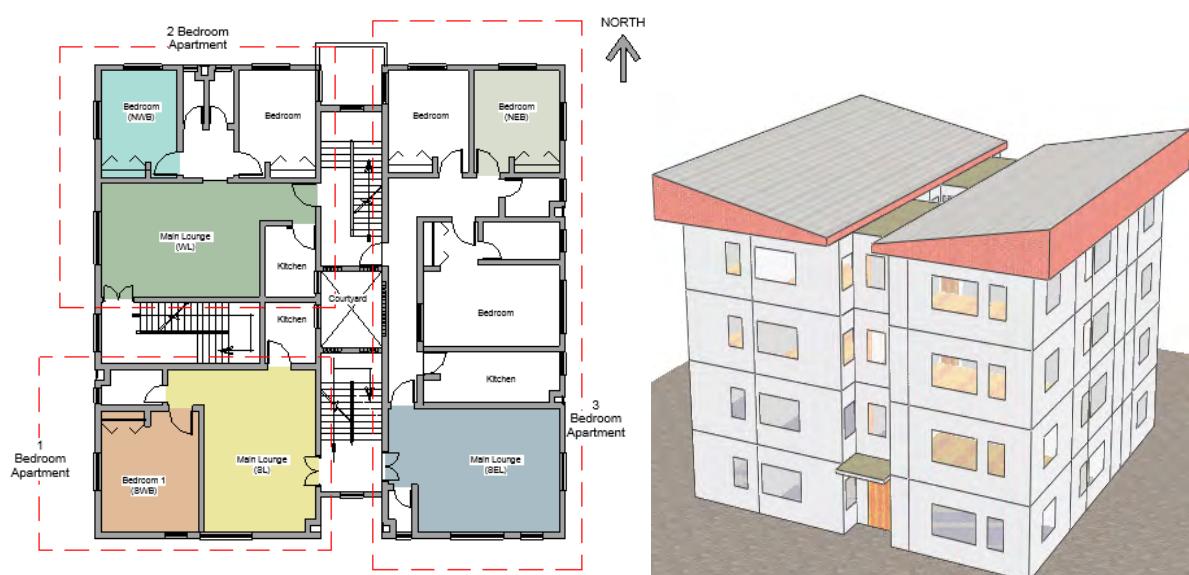


Figure 2. Selected analysed spaces and 3D view of Lagos HOMS thermal simulation model in IES-VE

### **Base Case Study**

The base case study investigated the current thermal performance of building to the present climate and its effects on thermal comfort. The dynamic building simulations consisted of 4 different cases and simulated under the existing building envelope. The assumptions made for the base case study simulation are presented in Table 1.

Table 1. Base case study general assumptions

Weather file	EnergyPlus weather data of Lagos (Lat. 6.45°N Long. 2.4°E Altitude 3m).
Calendar	The simulations were conducted for 8760 hours of a typical year
ventilation and Infiltration rates	Natural Ventilation = 5ACH Infiltration rate = 1ACH
Occupants	1 people were assumed for all the bedrooms. One bedroom apartment Living room = 1 occupant. Two bedroom apartment Living room = 2 occupants. Two bedroom apartment Living room = 3 occupants
Occupants heat gains	the heat gain assumed for each person in the living room was 75 W and the latent heat gain of 55 W while for bedrooms, sensible heat gain of 65 W and the latent heat gain of 30 W.
Construction U-Values(W/m <sup>2</sup> K)	Wall= 3.12, Floor= 2.33, Roof (covering, air space and ceiling) = 3.0 Single glazed Window = 5.59
Lighting	5w/m <sup>2</sup> for the bedrooms and living room respectively
Equipment	Living rooms and bedrooms were 10w/m <sup>2</sup> and 5w/m <sup>2</sup> respectively regardless of the apartment.
Comfort temp. range	23.5°C - 28.5°C
Cooling set point	No cooling and auxiliary cooling system

### Results and discussions

The base case study LHA0 presented a high degree of overheating under the current building fabrics. All the rooms were out of comfort temperature for an average of 67% of a typical year. This base case shows that the existing building fabric performed woefully without internal gains and the current climate scenario. To understand the impact of the occupancy, case LHA01 showed the rooms were out of comfort temperature for an average of 76.4% which is 4.5% higher than LHA0. Further analysis to assess the influences of lighting and equipment's gains, case LHA02 presented much worse overheating and period out of comfort temperature reached an average of 76.4% of a typical year. This showed that internal gain can increase the base case LHA0 by 14.03%.

The case with ventilation, LHA03 presented a significant improvement in the period within the comfort zone and it is noted that all the room reached an average of 55% in comfort zone. This indicated 84.03% improvement of LHA0 period within comfort temperature and 41.04% reduction in time outside comfort zone in a year. Figure 3 shows the summary of the base cases on the period in comfort temperature.

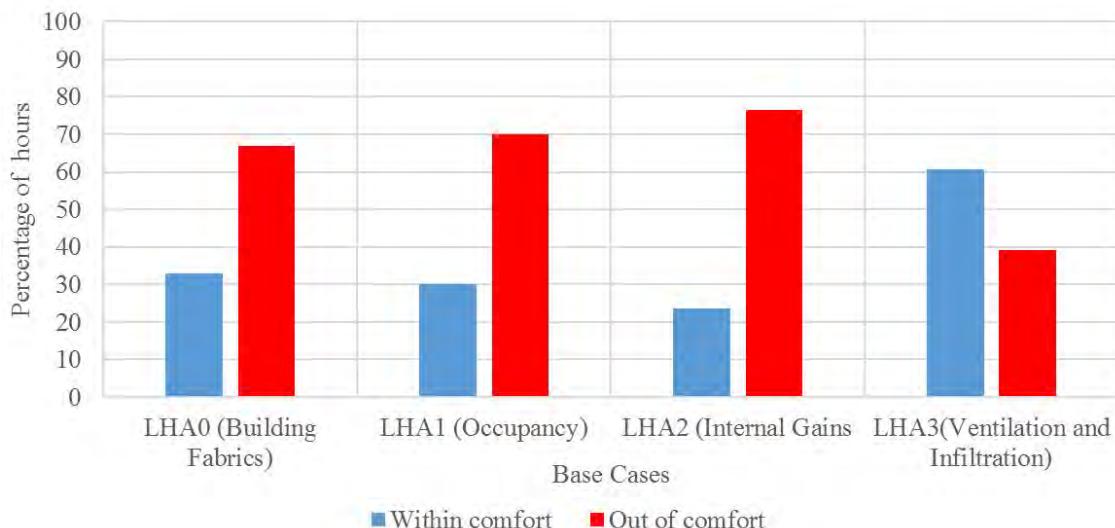


Figure 3. Percentage of time within and above comfort zone for all base cases

## Lagos Homs in Future Weather Scenarios 2050 And 2080

This examines the impact of projected future climate change scenarios of 2050 and 2080 respectively on thermal comfort using the existing building fabric, occupancy, lighting and equipment loads, and ventilation on the internal temperature. The methodology of sensitive analysis was employed to have a critical understanding of the building performance to the future weather condition using dynamic simulation.

### **Simulation Future Weather Data and Assumptions**

The future weather data of Lagos was generated by transforming present EnergyPlus weather (EPW) data into future data of 2050 and 2080 respectively using the morphing methodology in the climate change world weather file generator. It uses IPCC TAR model summary data of the HadCM3 A2 experiment for use in building performance simulation programs (Jentsch, et al., 2013). The morphing methodology used by this tool is based on the methods developed by Belcher, et al. (2005). All assumptions made in Table 1 remain the same except the weather file that was obtained from EnergyPlus weather data of Lagos morphed into weather data for 2050 and 2080.

### *Results and discussions*

The sensitive study of the future performance of Lagos HOMS in 2050 and 2080 respectively, presented a severe degree of overheating under projected future climate change scenarios. The future performance of the building envelope in 2050 showed an average of 90% of the year out of comfort temperature. With the internal gains, it showed a significantly more adverse impact on the indoor temperature with an average of 92% above comfort temperature. The 2050 future case showed no distinctive improvement with the addition of ventilation and infiltration rates. During the warmest period, the internal temperature of the rooms reached an average of 35.84°C.

Further sensitive analysis of 2080 future climate presented more severe overheating period. The envelope performed woefully in the absences of internal gains with an average 99.6% of the year out of comfort temperature. The introduction of internal gains resulted in a more degree of overheating in all the rooms with an average of 100% out of comfortable indoor temperature. With the addition of ventilation and infiltration rates, the rooms were still affected by severe overheating with an average of 99.95% out of comfort temperature. On the warmest period, the average temperature of rooms reached 39.79°C.

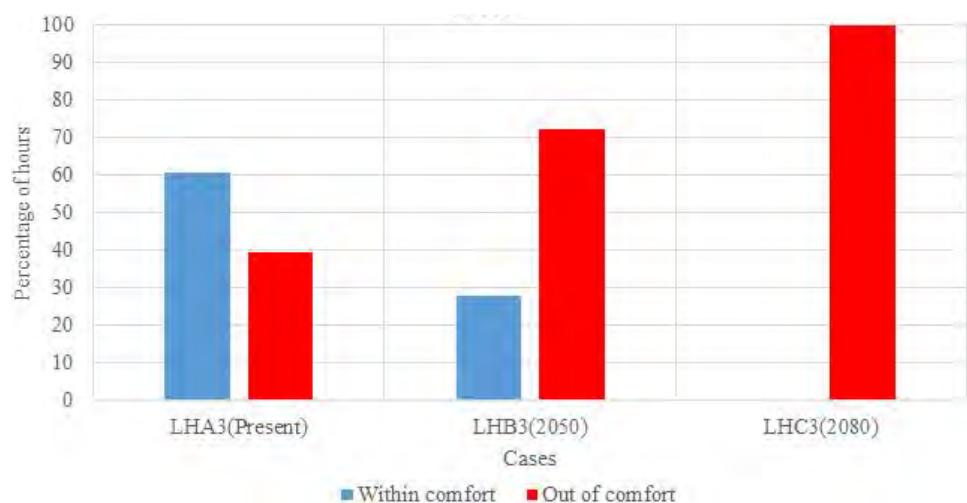


Figure 4. Percentage of time within and out of comfort temperature in present and future climate scenarios

## Optimisation Study of Lagos Homes Building Fabrics

This study investigated the most sensitive building fabrics in terms of the corresponding percentage of time in comfort temperature to establish a resilient building envelope to the changing climates as the existing building envelope presented a bad performance to the current and future weather scenarios.

The methodology of sensitive analysis of different building envelope of the wall; roof, floor and window thermal properties were carried out. The simulation is divided into 4 sections consisted of 24 different simulation studies of the current and the future years (2050 and 2080) as illustrated in Table 2. The assumptions were retained from the current and future studies except for the construction material details and thermal properties presented in Table 2.

Table 2. Simulation matrix of building fabrics optimisation and construction U-value of improved fabrics

Building Fabrics Optimisation	Construction U-Values W/m <sup>2</sup> K	Present	2050	2080
		A	B	C
Wall	W1- 500mm thick 2 layers hollow block (1.62)	AW1	BW1	CW1
	W2- 355mm thick hollow block with 100mm EPS insulation (0.39)	AW2	BW2	CW2
	W3- 450mm thick insulated block wall with 250mm EPS (0.15)	AW3	BW3	CW3
Roof	R1- Aluminium foil roof insulation (0.48)	AR1	BR1	CR1
	R2- Insulated roof ceiling with 25mm EPS (0.45)	AR2	BR2	CR2
	R3- Insulated roof and ceiling (0.35)	AR3	BR3	CR3
Glazing	24mm thick double glazing with 12mm cavity (1.6)	AG	BG	CG
Combination of best (wall + roof+ glazing)		AC	BC	CC

## Results and discussions

The optimisation of wall a slight improvement in the percentage of time in comfort temperature for the present-day and 2050 but presented a significant improvement in 2080. There was a significant reduction of 12.2% in 2080 percentage of time above.

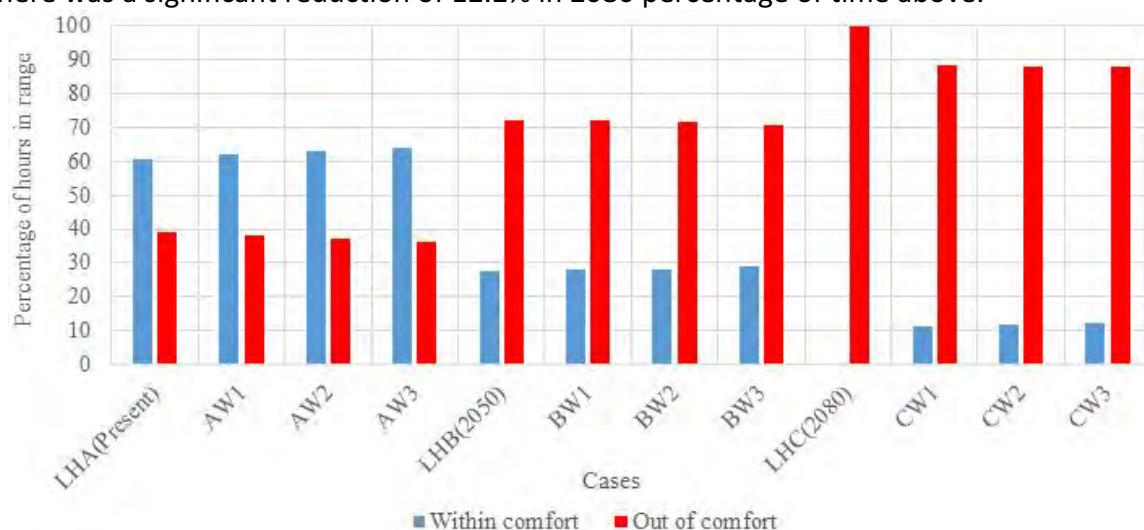


Figure 5. Wall optimisations percentage of time in and out of comfort for the present and future cases

The optimisation of the roof especially the increase in insulation level of the ceiling showed less improvement to the present condition but gave a significant reduction in the time above comfort temperature for the future cases. Potential increase in the roof insulation to the Passive House standard might increase the percentage of time in comfort.

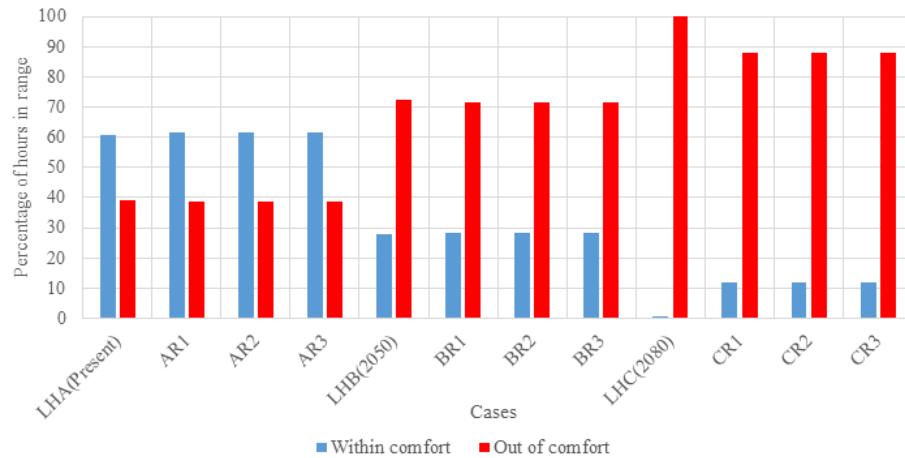


Figure 6. Roof optimisations percentage of time in and out of comfort for the present and future cases

The improvement to double glazing showed a negligible improvement to present-day and future percentage of time in comfort temperature. Despite the slight improvement, the most sensitive building fabrics are the wall and the ceiling.

The combination of all the building fabric optimisation showed a minimal improvement in the time within comfort temperature for the present and 2050 future scenarios but presented a noticeable improvement in time within comfort zone for 2080 future scenario.

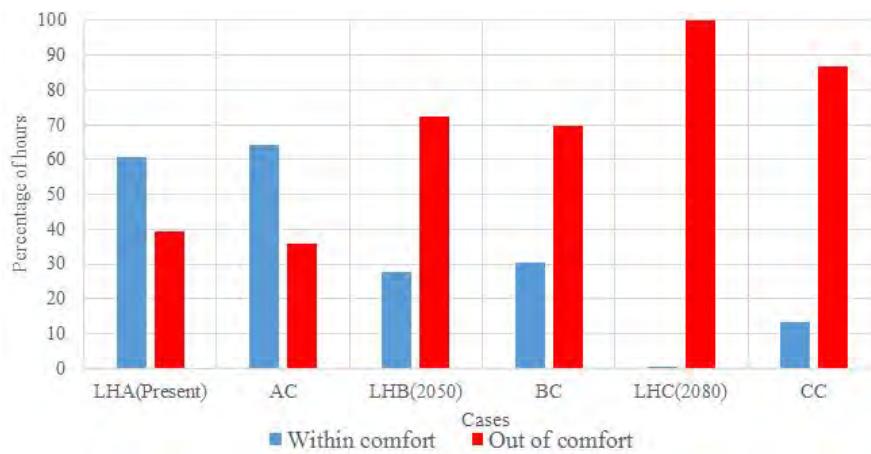


Figure 7. Combined optimisations percentage of time in and out of comfort for the present and future cases

## Conclusion

This study outcome is derived from the dynamic simulation results of Lagos HOMS in different climate scenarios. The current performance of the building presented a high degree of overheating period under the current building envelope. The addition of internal gains resulted into more severe overheating period, it is important to put off appliances and lighting fixtures to improve the period in comfort temperature. It was noted that the weekends are most overheating days during the warm period because the internal gains are higher as a result of full occupancy schedule. The introduction of ventilation reduced the time out of comfort significantly.

The study of projected future climate scenarios indicated a very low performance of the current building envelope with more severe overheating for all times of the year. Also, the addition of the ventilation and infiltration have lesser effects on both 2050 and 2080 percentage of time in comfort temperature as contrary to the positive impact of ventilation rate under current weather situation.

Furthermore, the study of optimisation of the building envelope using fabric first approach presented a slight improvement in the percentage of time in comfort temperature under Lagos present-day and future case 2050 but gave a significant improvement in 2080. Despite the slight improvement of building envelope optimisation, the most sensitive building envelopes are the wall and the roof.

Conclusively, the optimisation of the building envelope is an important passive strategy to improve the comfort period, occupants' health and reduce the energy consumption and the cost of maintaining gasoline and diesel power generators in changing climate. Further study should be carried out on other passive strategies to improve the period in changing climate scenarios.

## Acknowledgment

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## References

- Atuma, U., 2016. Uncommon heat wave on the prowl. [Online] Available at: <http://sunnewsonline.com/uncommon-heat-wave-on-the-prowl/> [Accessed 20 July 2016].
- Belcher, S. E., Hacker, J. N. & Powell, D. S., 2005. Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, 26(1), pp. 49-61.
- Beniston, M. et al., 2007. Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change*, 81(1), p. 71–95.
- Christensen, J. et al., 2007. : Regional climate projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY, USA: Cambridge University Press.
- Dumo, E. & Olajide, E., 2016. Frustration, anger as heat wave worsens Nigerians' misery. [Online] Available at: <http://punchng.com/frustration-anger-as-heat-wave-worsens-nigerians-misery/> [Accessed 20 07 2016].
- Huth, R., Kyselý, J. & Pokorná, L., 2000. A GCM simulation of heatwaves, dry spells and their relationship to circulation. *Climate Change*, 46(2000), p. 29–60.
- Jentsch, M. F., James, P. A., Bourikas, L. & Bahaj, A. S., 2013. Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. *Renewable Energy*, Volume 500, pp. 514-524.
- Joshi, M. et al., 2011. Projections of when temperature change will exceed 2°C above pre-industrial levels. *Nature Climate Change*, 1(8), pp. 407-412.
- Kazeem, Y., 2016. An unusually intense Lagos heatwave reminds Nigerians they are not ready for climate change. [Online] Available at: <http://qz.com/628387/an-unusually-intense-lagos-heatwave-reminds-nigerians-theyre-not-ready-for-climate-change/> [Accessed 18 July 2016].
- Levermore, G., Chow, D., Jones, P. & Lister, D., 2004. Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK, UK: Tyndall Centre Technical Report 14.
- Li, Y. & Zhao, X., 2012. An empirical study of the impact of human activity on long-term temperature change in China: A perspective from energy consumption. *Journal of Geophysical Research*, Volume 117.
- Sailor, D., 2011. A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. *International Journal of Climatology*, 31(2), pp. 189-199.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Effectiveness of passive climate adaptation measures in residential buildings in Germany

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**Abstract:** Current climate scenarios indicate that, summer and winter periods in Germany will get warmer and milder, respectively by 2090. This will affect the energy demand and the thermal comfort of the buildings' inhabitants. Whereas milder winters will reduce the heating demand, warmer summers will increase the overheating potential of the buildings. The resulting discomfort during summer could lead to an increased potential for active cooling and therefore to additional CO<sub>2</sub> emissions. This topic is investigated in a detached single family house which represents a large part of the German building stock. In order to reduce the potential cooling demand of the single family house, three passive climate adaptation measures: solar protection glazing, shading, and natural ventilation were combined and assessed. These measures were quantified with a dynamical thermal building simulation tool for the periods 2030-2060 and 2060-2090, by assessing the performance indicators: overheating degree hours, heating and cooling demand, and CO<sub>2</sub> emissions. The results demonstrate that a combination of automated blinds and ventilations can significantly reduce the overheating degree hours and the potential cooling demand. Furthermore, they illustrate the necessity to consider passive measures in a state of art refurbishment of existing buildings.

**Keywords:** Passive climate adaptation measures, climate change, building energy simulation, energy consumption, overheating

### Introduction

The Fifth Intergovernmental Panel on Climate Change report shows that even if anthropogenic CO<sub>2</sub> emissions are reduced, climate change still takes place (IPCC, 2013). In Germany, climate change scenarios based on the IPCC report indicate that an increase of temperature between 2 and 5°C is to be expected in the year 2090 compared to 2000 (Jacob *et al.*, 2012). This rising temperature will result in milder winters and hotter summers. While milder winters potentially reduce the energy demand for heating, hotter summers might increase the overheating potential of buildings and thus lead to a higher need for active cooling. However, since the majority of the residential buildings in Germany is not equipped with active cooling systems (machine cooling), the likelihood of retrofitting and thus increase in energy demand is high.

The building sector accounts for about 30% of anthropogenic greenhouse gas emissions in Germany (Bürger *et al.*, 2016). The building sector not only impacts climate change, it will be also affected by it in the future. It is therefore important to analyze the future climatic conditions and to assess buildings' energy performance with respect to climate change mitigation and adaptation. The refurbishment cycle of buildings averages between 30 and 60

years (Nemeth, 2011), which means that buildings that are refurbished today will be impacted by climate change in the future. Therefore, both existing and new buildings should adapt to the changing climatic conditions to ensure the thermal comfort of their occupants.

The focus of this paper is on non-active cooling systems, since equipping buildings with active systems will lead to an increased energy demand which results in more CO<sub>2</sub> emissions and thus accelerating the climate change. A sustainable approach to avoid this increased energy demand is through passive climate adaptation measures.

In this study, the effectiveness of three passive climate adaptation measures will be evaluated in a detached single-family house, which is representative of a large share of the German building stock. Only passive measures are investigated, as they do not directly contribute to an increased energy consumption and higher CO<sub>2</sub> emissions. It is assumed that the case study will be retrofitted according to the German law. Therefore, the goal of this study is to optimize the refurbishment with passive measures, which can be implemented in any conventional refurbishment in order to adapt it to the changing climate. Several publications investigated the effectiveness of passive climate adaptation measures on both residential and commercial buildings in North-Western European countries (Hamdy and Hensen, 2015; Porritt *et al.*, 2013; van Hooff *et al.*, 2014). They studied a range of possible climate change adaptation measures, and showed that not all of them were equally effective. This study, therefore, will focus on three of the most effective adaptation measures based on the mentioned studies. The investigated measures are: solar protection glazing, shading, and natural ventilation.

To include climate change in the analysis, weather data from the regional climate model REMO (Jacob *et al.*, 2012) are used as boundary conditions for simulation until the year 2090.

In the next section, the methodology of this study will be addressed, after which the results of the investigation will be analyzed and discussed and in the end, a conclusion will be drawn.

## **Methodology**

In this study, the evaluation of the passive adaptation measures is carried out with a dynamical thermal building simulation tool. For this purpose, the software tool IDA ICE was used (EQUA, 2013). Although numerous simulations are required for this work we can simplify the process by linking the IDA ICE program to the statistical program R (Venables and Smith, 2016) to parallelize the simulations, which leads to lower computation times.

### ***Investigated building type***

Detached single-family houses are the most common residential buildings in Germany. Therefore, a detached single-family house in Neuauing-Westkreuz, Munich, was selected for this study. Fig. 1 shows the floorplans and the building facades. This building has a floor area of 147 m<sup>2</sup> and a heated building volume of about 389 m<sup>3</sup>.

For the case study, it is assumed that the building built in the 1950's will be refurbished according to the German law EnEV (EnEV, 2014). State of the art rules and regulations in Germany (for example the EnEV) do not consider the long-term impact of climate change, because they are just used as a proof of concept for different types of buildings. This study, however, focuses on the need to assess passive measures to adapt refurbishments to the changing climate. The construction details according to the German law are summarized in Table 1. This refurbishment represents the base case, which is then optimized with the passive measures.



Figure 1. Facades, floor plans of the detached single-family house in Neuauing-Westkreuz, Munich.

Table 1. Base case construction details based on EnEV 2014

U-value External Walls [W/m <sup>2</sup> K]	U-value roof [W/m <sup>2</sup> K]	U-value internal floor [W/m <sup>2</sup> K]	U-value Window [W/m <sup>2</sup> K]	g-value Window [-]	T <sub>vis</sub> -value window [-]	Shading system
0.24	0.24	0.3	1.3	0.6	0.8	-

### Combined passive climate adaptation measures

In order to increase the effectiveness of the above mentioned passive measures, these methods are combined. Another reason for the creation of these combinations is the requirement of the standard DIN 4108-2:2013-02, which regulates thermal building simulations to protect buildings from overheating in Germany. This standard requires high rates of natural or mechanical ventilations before using sun protection systems like sun protection glazing or shading systems. Therefore, three combinations are created in which the ventilation hours are higher compared to the base case (see Table 2).

The economical combination is based on a solar protection glazing and a natural ventilation. For this purpose, only a sun protection glazing with a low g-value of 0.2 [-] is used in the refurbishment (hence the name economical). The building is ventilated by a maximum natural ventilation driven by the user. Due to the low g-value of the sun protection glazing, this combination increases the heating demand, which is a negative side effect. The moderate combination is created for the reduction of this negative side effect. In this combination, a sun protection glazing with a higher g-value of 0.35 [-] is used. Like the economical combination, this combination is also ventilated by a maximum natural ventilation. Additionally, an automated shading blind is installed to optimize the solar gains in summer without affecting the heating demand in winter. The intelligent combination avoids the negative effect of the increasing heating demand of the two other combinations, by not replacing the glazing during the refurbishment. For reducing the solar gains in summer, a

shading system is installed on the windows. In addition, an automated window ventilation is used, which runs all day. When the outside temperature rises above 26°C, this device is turned off. The intelligent combination is therefore completely automated by the use of the shading system and the automated window ventilation.

Table 2. Combined passive adaptation measures investigated

Combination	g-value [-]	F <sub>c</sub> -value [-] <sup>(1)</sup>	g <sub>tot</sub> -value [-] <sup>(2)</sup>	T <sub>vis</sub> -value [-] <sup>(3)</sup>	Window Ventilation
Base case	0.6	1	0.6	0.8	Minimum by user (7:00 - 7:30 & 21:00 - 23:00 h)
Economical	0.2	1	0.2	0.35	Maximum by user (23:00 - 7:30 & 12:00 - 15:00 h)
Moderate	0.35	0.3	0.1	0.6 <sup>(4)</sup>	Maximum by user (23:00 - 7:30 & 12:00 - 15:00 h)
Intelligent	0.6	0.25	0.15	0.8 <sup>(4)</sup>	Automated (all day, only when θ <sub>op</sub> ≥ θ <sub>amb</sub> and θ <sub>amb</sub> ≤ 26°C) <sup>(5)</sup>

(1) F<sub>c</sub>-value is the multiplier for the drawn shading

(2) The g<sub>tot</sub>-value represents the reduced solar energy entering the building through the window, when the shade is drawn, and is calculated by the following formula: 
$$g_{tot} = g \times F_c$$
 Formula (1)

(3) T<sub>vis</sub>: visible light transmittance degree values according to (Keller *et al.*, 2011)

(4) The T<sub>vis</sub>-values are only valid when the shading system is lifted

(5) θ<sub>op</sub> = Operative temperature, θ<sub>amb</sub> = Ambient temperature

### Building simulation parameters

The parameters used in the building simulation are summarized in Table 3.

Table 3. Building simulation parameters

Parameter	Values		
Maximum ventilation rate during days (when θ <sub>op</sub> * ≥ 23°C)	- 3 [h <sup>-1</sup> ] (from 6 a.m. to 23 p.m.)		
Maximum ventilation rate during nights (when θ <sub>op</sub> ≥ 23°C)	- 2 [h <sup>-1</sup> ] (from 23 p.m. to 6 a.m.)		
Shading is activated when solar radiation on the window is higher than the value:	- 200 [W/m <sup>2</sup> ] (North, northeast, northwest direction) - 300 [W/m <sup>2</sup> ] (All other directions)		
Infiltration	0.1 [h <sup>-1</sup> ]	Heating set point	21 [°C]
Internal heat gains	4 [W/m <sup>2</sup> ]	Cooling set point	26 [°C]
short wave reflectivity of the facade	0.5 [-]	Presence time	24 [h/d]

### Climate Data

For the investigation, weather data are generated from the regional climate model REMO (Jacob *et al.*, 2012), which has a temporal resolution of one hour. The climatic scenario A1B was chosen because it represents a moderate development of the climate change scenario (IPCC, 2013).

The climate data is subdivided into the three periods: 2000-2030, 2030-2060, and 2060-2090. Since we are now in the first period (2000-2030) and assume that the dwelling is being refurbished in the present with a refurbishment cycle of 30-60 years (Nemeth, 2011), we study the impact of climate change on the building over the remaining periods (period 2030-2060 and 2060-2090). The data include the following parameters: outside air temperature, relative humidity, solar radiation wind direction and the wind speed.

## Results and discussions

### Overheating Degree hours

In the first step, the overheating degree hours for the base case and combinations were calculated in the investigated periods. The overheating degree hour ( $Gh_{26}$ ) is calculated from the operative temperature ( $\theta_{op}$ ) by the following formula, according to DIN 4108-2:2013-022:

$$Gh_{26} = \sum (\theta_{op} - 26^\circ\text{C}) \quad \text{when } \theta_{op} \geq 26^\circ\text{C} \quad \text{Formula (2)}$$

For the calculation according to DIN 4108-2:2013-02, standard test reference years should be used. However, in this study the REMO climate model is used for the investigation, which does not follow the prescriptions of the regulation. Therefore, this regulation is just used for estimating the risk of overheating and comparing the risk in the investigated periods.

Figure 2 shows the reduction of the overheating degree hours through the use of the combinations in the periods 2030-2060 and 2060-2090 compared to the base case. Each boxplot shows the results of the 30 years simulated in the period. For each floor plan the zone with the highest overheating degree hours is presented (Living 2 in ground floor and bedroom 1 in first floor, see Figure 1). The standard DIN 4108-2 prescribes overheating degree hours under 1200 Kh/a, as shown by the red lines. In the period 2030-2060, the required value is complied to by all the combinations. In the period 2060-2090, the overheating degree hours are also significantly reduced in comparison to the base case but the requirement value cannot be kept by the combinations in this period.

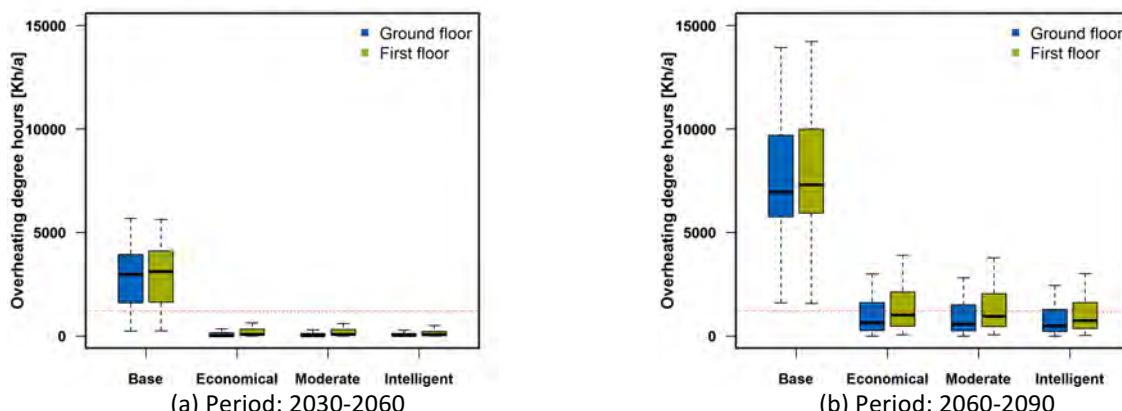


Figure 2. Number of degree hours for the detached single house in the base case and combinations

### Heating and cooling demand

Figure 3 shows the yearly heating and cooling demand in the investigated periods for the combinations in comparison with the base case. Figure 3 (a) shows that the economical combination leads to an approximately 20% increase in the heating demand in both periods. The moderate combination results in only a 10% increase in the heating demand. Only the intelligent combination solves this problem with an unchanged heating demand compared to the base case, as the glazing is not changed in this combination.

The potential for active cooling could be significantly reduced in both periods with using the combinations (see Figure 3 (b)). The potential cooling attains very low results in the period 2030-2060 (under 1 kWh/m<sup>2</sup>a), so that in reality, machine cooling can be avoided if the combinations are used. However, the potential for active cooling increases in the last period, which leads to necessitated machine cooling systems during this period. The results show that the moderate and economical combination are equally effective in reducing the cooling

demand. The effectiveness of the intelligent combination increases in comparison with the two other combinations in the last period. In order to justify this effectiveness, the climate data of both periods have been analyzed more precisely. The analysis shows that in the last period the annual average ambient temperature will increase by almost 20% in comparison to the period 2030-2060. The solar radiation will increase by just 3% in the later period. This means that the increased outside temperature is the reason behind the higher cooling demands. As the intelligent combination is based on an automated ventilation which ventilates all day only when  $\theta_{op} \geq \theta_{amb}$ , and  $\theta_{amb} \leq 26^\circ\text{C}$ , it operates more efficiently in the last period compared to the other two combinations, which are based on a user-activated ventilation. It must be considered that the investigated climate model is just a prognosis for the future climate. Therefore, other climate scenarios from the REMO model can differ in the results regarding the rising outside temperature and solar radiation.

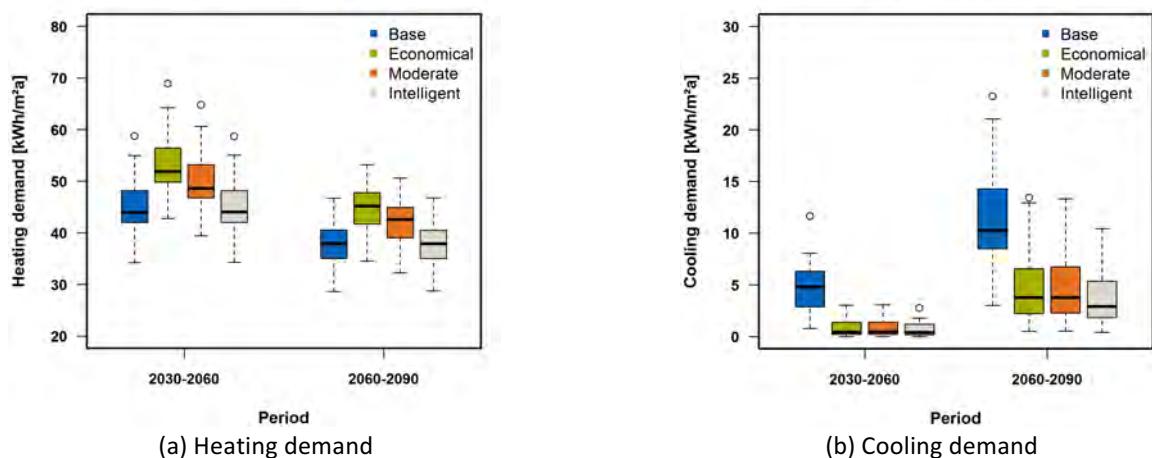


Figure 3. Yearly heating and cooling demand for the detached single house in the base case and combinations

#### **Greenhouse gas emissions ( $\text{CO}_2$ equivalent emissions)**

Despite the significant reduction of the potential cooling demand, this demand could not be avoided in the later period. Therefore it is important to find out to what extent greenhouse gas emissions can be saved by the use of the combinations if a machine cooling system would also be used in the building. For this reason, two different machine cooling systems and their  $\text{CO}_2$  equivalent emissions were analyzed (see Table 4).

Table 4  $\text{CO}_2$  equivalent scenarios

	Scenario 1	Scenario 2
Specification	Efficient heating + inefficient cooling $\eta = 0.9$ ; 0.02 [KgCO <sub>2</sub> eq/kWh]	Efficient heating + efficient cooling $\eta = 0.9$ ; 0.02 [KgCO <sub>2</sub> eq /kWh]
Heating		
Cooling	COP = 2.5 ; 0.535 [KgCO <sub>2</sub> eq /kWh]	COP = 4.5 ; 0.535 [KgCO <sub>2</sub> eq /kWh]

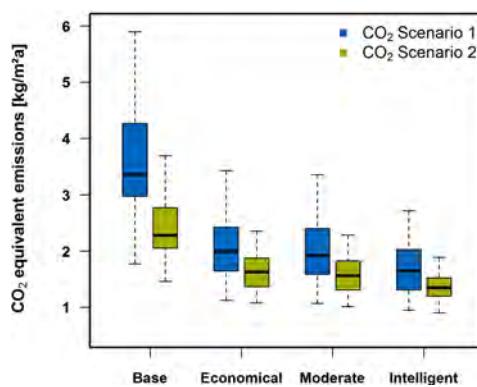


Figure 4.  $\text{CO}_2$  equivalent scenarios for the detached house in the period: 2060-2090 (see Table 4)

The results show a reduction of greenhouse gas emissions above 40% through the use of the combinations (Figure 4). The graphic illustrates that the use of passive measures in combination with an inefficient cooling system is more effective than using an efficient cooling system without using passive measures.

## Conclusions

This study analyzed the performance of three combinations of passive adaptation measures using dynamical thermal building simulations to adapt refurbishments to the changing climate. The following conclusions can be made out of this study:

(1) Today's refurbishments can be optimized by passive measures with little increased effort so that the buildings can be adapted to the changing climate. The use of passive measures makes it possible to significantly increase the thermal comfort of the inhabitants.

(2) The results showed that the additional demand for active cooling can be eliminated through the use of passive measures in the period 2030-2060. However, this demand cannot be completely prevented in the period 2060-2090. Still, for the examined residential building, the results showed a reduction of the cooling demand for this period by more than 50% in comparison to a refurbishment according to the current German law.

(3) As potential cooling demand could not be avoided in the period 2060-2090, two scenarios with machine cooling systems were investigated to evaluate the effectiveness of the passive measures. The application of passive measures in combination with an inefficient cooling system proved to be more effective than the application of an efficient cooling system without using passive measures. Therefore, a positive impact on both climate mitigation and climate adaptation could be achieved through the use of passive adaptation measures.

Today, as the refurbishment cycles of buildings average between 30 and 60 years (Nemeth, 2011), it is already necessary to implement passive adaptation measures in refurbishments. It was shown that the use of a sun protection system in combination with natural ventilation is sufficient to prevent the overheating problem in the period 2030-2060. In the period 2060-2090, the need for an automated window ventilation increases. This indicates that in today's refurbishments, the use of a shading system or a sun protection glazing for overheating protection is a priority. Other measures like the automated ventilation can be used for additional refurbishments in the future, to make the buildings more effective against the overheating problem due to climate change.

## Limitations and future work

This investigation is based on the prognosis of the climate scenario A1B from the REMO model. Since the probability of occurrence of alternative climatic scenarios is the same (IPCC, 2013), further examination of the alternative climatic scenarios would be necessary. This allows a more detailed and accurate assessment of the results in the light of uncertainties in the future climate.

Secondly, the present study only examined the German law (EnEV 2014) as the refurbishment standard investigated. A higher insulation standard such as the passive house should be assessed in future works as a proof of concept.

Thirdly, the investigations carried out are based on refurbishments of existing buildings. However, it must be borne in mind that the results of this study should also be investigated on new buildings because the requirements for the standard according to EnEV and DIN 4108-2:2013-02 are mandatory for new buildings in Germany. Therefore, the necessity of using

passive measures must also be taken into account in the planning process for new buildings. Additionally, other building types should be investigated in future works.

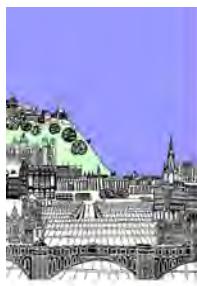
The use of green infrastructure (for example trees, green roofs, and green facades) provides shading of the open space and building walls (Zölch *et al.*, 2016). Accordingly, a simultaneous assessment of the building and the greening situation outdoors can be taken into account for further optimizations.

## Acknowledgments

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## References

- Bürger, V., Hesse, T., Quack, D., Palzer, A., Köhler, B., Herkel, S. and Engelmann, P. (2016). *Klimaneutraler Gebäudebestand 2050*. Dessau-Roßlau: Umweltbundesamt.
- DIN 4108-2:2013-02 (2013). *Thermal protection and energy economy in buildings - Part 2: Minimum requirements to thermal insulation*.
- EnEV (2014). *Energieeinsparverordnung 2014*.
- EQUA (2013). *Handbuch IDA ICE - IDA Indoor Climate and Energy 4.5*. Solna: EQUA Simulation AB.
- Hamdy, M. and Hensen, J. (2015). Ranking of dwelling types in terms of overheating risk and sensitivity to climate change, In: *Proceedings Building Simulation '15*, 7-9 December 2015. Hyderabad, India: IBPSA.
- IPCC (2013). Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge, United Kingdom: Cambridge University Press.
- Jacob, D., Bülow, K., Kotova, L., Moseley, C., Petersen, J. and Rechid, D. (2012). *CSC Report 6: Regionale Klimaprojektionen für Europa und Deutschland: Ensemble-Simulationen für die Klimafolgenforschung*. Available at: [http://www.climate-service-center.de/imperia/md/content/csc/csc\\_report6.pdf](http://www.climate-service-center.de/imperia/md/content/csc/csc_report6.pdf) (Accessed: 1 December 2016).
- Keller, B., Rutz, S., Antón, I., Bernasconi, R., Gebhard, H., Guha, F., Günther, P. and Magyari, E. (2011). *Pinpoint - Fakten der Bauphysik zu nachhaltigem Bauen*. 2<sup>nd</sup> edn. Zürich: vdf Hochschulverlag.
- Nemeth, I. (2011) *Methodenentwicklung zur Bestimmung von Potenzialen der Energieeffizienzsteigerung im Haushalts und GHD Sektor*. Doktorarbeit. Technische Universität München.
- Porritt, S.M., Cropper, P.C., Shao, L. and Goodier, C.I. (2013). Heat wave adaptations for UK dwellings and development of a retrofit toolkit. *International Journal of Disaster Resilience in the Built Environment*, 4(3), pp. 269–286.
- van Hooff, T., Blocken, B., Hensen, J. and Timmermans, H. (2014). On the predicted effectiveness of climate adaptation measures for residential buildings, *Building and Environment*, 82, pp. 300–316.
- Venables, W.N. and Smith, D.M. (2016). *An Introduction to R: Notes on R: A Programming Environment for Data Analysis and Graphics*. Available at: <https://cran.r-project.org/doc/manuals/r-release/R-intro.pdf> (Accessed: 8 December 2016).
- Zölch, T., Maderspacher, J., Wamsler, C. and Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale, *Urban Forestry & Urban Greening*, 20, pp. 305–316.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Adapting cities to climate change: incorporating the knowledge and practices of urban professionals in a design-aid tool

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**Abstract:** Urban practitioners can be key actors for climate change action through city development. However, adaptation and mitigation are insufficiently integrated in current design practices. The CapaCity research project hypothesize that this is partially due to lacks of knowledge-transfer. Its goal is therefore to develop a prototype design-aid tool for enhancing a project's adaptive character, with particular focus on practitioners-usability. The first phase included a series of consultations with professionals working in Toulouse (France) through a survey and two design workshops. The aim was to assess how they address climate change in a development project, and their use of tools in a design process. The results are presented here. Evaluation-tools were very little used. Moreover, the findings indicated that a solution-based design approach is common among practitioners, and that main sources of knowledge are initial education and professional experience. A design-aid tool should reflect design practices, and be an educational-tool to support practitioners' 'learning by doing'. The second part of the paper describes the structure of the suggested approach: a web application to guide practitioners following three common stages of an urban project (diagnostic, program, and design) recommending methods, adaptation solutions, and concrete examples relevant to users' specific projects.

**Keywords:** climate adaptation, practitioners, design, education, design-aid tool.

### Introduction

City life and its resulting greenhouse gas emissions (GHG) contribute greatly to climate change, but urbanization also holds solutions. One strategy is to introduce mitigation and adaptation measures through urban and building development (Gunawansa and Kua, 2014; Kleerekoper et al., 2012; Shaw et al., 2007; Smith et al., 2013; de Wilde and Coley, 2012). Urban designers and architects can be key actors to achieve this. However, studies indicate that climate change is insufficiently integrated in design practices. (Dubois, 2014). In part, because tools developed by research tends to fail to respond to designers' actual needs, and so remain little incorporated in design projects (Bierbaum et al., 2013; Dilling and Lemos, 2011; Harries and Penning-Rowsell, 2011; Horvat et al., 2011; McAndrews et al., 2013). According to Lemos and colleagues (2012: 789), what scientists see as useful information does not necessarily correspond with what professionals see as useful. Designers have a

particular way of knowing and problem-solving (Cross, 2006; Lawson, 2006a, 2007; Schön, 1983), which must to be addressed more adequately by the scientific community.

The research project CapaCity: from Concepts to Action for a Proactive Adaptation of Cities, seeks to address these and other disparities research-practice in order to fill the gap between the two. Its objective is to develop a prototype design-aid tool to support practitioners towards adaptive urban projects. For this tool to be understandable and usable for practitioners, gaining insights from design practices was important. In order to do so, a two-fold study was conducted in 2015. The objectives were to: i) assess current the knowledge among city and building professionals with regards to climate change adaptation, ii) examine how they consider, seek, and apply knowledge from different sources, and iii) observe a climate adaptive design process. The results from these enquiries guided the development of the prototype tool, which is currently being finalized. This paper presents main findings, and their implication for the suggested prototype tool.

### **Theoretical framework**

There are important gap between research and practice (Kirkeby, 2012; Lawson, 2013; Skogheim, 2008). As a result, studies have reported that research-based knowledge is little integrated in urban design processes, despite its proven necessity with regards to climate adaptation and mitigation (Tennøy, 2012). Research produces so-called context-independent knowledge, while design is strongly context-dependent (Kirkeby, 2012; Lawson, 2013; Skogheim, 2008). This can render research-based knowledge seemingly unapplicable in design projects. Practitioners tend to apply a solution-based approach to tackle design problems. The exploration of potential solutions produces a deeper understanding of the project at hand (Darde, 1979; Kirkeby, 2012; Lawson, 2006a), contributing to detect interdependencies between different aspects of a problem. This allows professionals to go beyond the client's brief, and to identify potential issues and challenges not addressed by the latter, in order to establish what the problem 'really is'. This is consistent with the notion of "setting and framing the problem" (Rittel and Webber, 1973; Schön, 1983). The designers' knowledge of solutions builds over time, through various academic, professional, and personal experiences. Own experience, and that of their colleagues, remain the prime source for information, however (Kirkeby, 2012; Skogheim, 2008; Tennøy, 2012), for instance precedents, references, and types of form (Cross, 2006; Schön, 1988). Whole or partial solutions, they are a straightforward and pragmatic way to link problems to solutions, and to accelerate thinking (Augustin and Coleman, 2012). The designers' reliance on rules of thumb to rapidly evaluate the performance of an idea is another manifestation of this solution-based knowledge (Lawson, 2006b).

In a longer perspective, a better understanding by the scientific community of designers' particular way of knowing (solution-focused, experience-based and context-dependent) could help bridge the gap between research and practice, and strengthen climate adaptation actions.

### **Method**

The first phase of the CapaCity-project focused on gaining an understanding of design practices, and the use of various tools, as well as information kinds and sources in a process. Therefore, a series of consultations with urban practitioners working in the Toulouse Region (France) were undertaken: an online survey and two design workshops.

### ***Online Questionnaire***

2660 email-invitations were sent to practitioners via three professional networks. The survey was composed of eleven questions, available through an online open source platform. 115 respondents anonymously completed the questionnaire, and the results were statistically processed. The first half provided an overall portrait of the respondents (age, sex, education, employment categories, professional experience, and typically project). The second half focused on: i) environmental issues considered in design projects, ii) data and tools employed in the design process, iii) qualities and shortcomings of existing design-aid tools.

### ***Design Workshops***

Design workshops were chosen as a method in order to observe how practitioners proceed when asked to design a neighbourhood adapted to the future climate of Toulouse. What do they actually know? What kind of information is sought? How and when are design-aid tools employed? Two workshops were held in May and in June 2015 at the Toulouse School of Architecture with eighteen urban practitioners from various educational and professional backgrounds, primarily architecture, planning, landscape architecture, and geography.

The workshops had two main parts: a one-hour session on adaptation in an urban context, followed by a two-hour design game where participants worked in multidisciplinary teams. A facilitator guided the game. The objective was to establish a proposal for an urban renewal project located in Toulouse, which had to be exemplary regarding climate change adaptation. The design brief specified 400 dwellings, 200 parking spaces, and one public place. The teams started with basic information about the project, and tools such as tracing paper and an aerial photo. Throughout the game they could access complementary data and resources using six playing cards. Three cards allowed consulting either “technical” or “technological” resources (e.g. simulation software). Three others offered a consultation with an expert (e.g. mobility or energy), or the client (a person from Toulouse Métropole). Unpredictable events could occur throughout as the facilitator had seven joker cards that would compel a team to integrate further climate adaptive objectives. Each team was filmed throughout the entire game. This was transcribed, and a content-analysis conducted focusing on: i) kinds of, and sources for, applied knowledge, ii) elements that influenced the process and/or shaped the design proposal, and iii) the nature of applied design solutions.

Design workshops come with methodological limits such as the relatively low number of participants (18), the short duration of the design game, and the challenge for participants to work on a project with new people from various disciplinary backgrounds and experiences. However, seen in light of the theoretical framework, the results provide satisfactory insights into design practices, and indications of practitioners’ actual needs, in order to nourish the development of a climate adaptive design-aid tool. Furthermore, during and after the workshop, participants underlined the parallels between the design game and an actual design process, thus confirming its relevance as an opportunity to observe them in action.

### **Consultation results**

The questionnaires and workshops provided a number of insights regarding architectural and urban design practices and processes, consistent with the literature review.

### ***First finding: sources of knowledge***

In the questionnaire, respondents were asked to range a list of tool-categories based on the occurrence of their use. Technical guidelines and standards for environmental quality (e.g. books, technical papers, websites) are ‘frequently’ consulted (60%). The majority of the respondents (92%) ‘not frequently’ or ‘never’ use numerical simulation tools (e.g. Pleïade-Combie, ArchiWIZARD, Ecotect, Dialux, IES). However, more than 50% stated to ‘frequently’ use *simplified* computation tools (e.g. Excel, rules of thumb, abacuses) in order to evaluate the performance of potential solutions. These results support previous studies on the topic (Dubois et al., 2015; Horvat et al., 2011).

During the workshops, the participants appeared to rely primarily on their own experience and education, or that of their fellow team-members, as source of knowledge. They were also more prone to choose direct, face-to-face access to knowledge (i.e. consulting experts), consistent with a study conducted by Kirkeby (2012). Indeed, despite the technical and technological resources available, all teams prioritized 10-minute discussions with the client and various experts. Computer tools on the other hand, were very little used, and if so, mainly to obtain information the experts could not provide. Interestingly, knowledge rooted in experience was primarily shared among the designers by referring to urban and architectural precedents and rules of thumb. This specific kind of knowledge aided several teams in imagining solutions for the future of Toulouse. One participant, for example, suggested the following idea based on a trip to Morocco: “They know in the Maghreb, how to deal with extreme heats: streets are deep and narrow, and canvas are sometimes stretched over public spaces to provide extra shade on the hottest days.” The most experienced participants were the main users of rules of thumb; a means to address operational issues, often allowing for a rapid estimation of the size of building blocks, streets, buildings, and parking.

### ***Second finding: a solution based approach***

During the workshops, all teams adopted a solution-based approach in order to address the complexity of designing a neighbourhood adapted to the future climate of Toulouse. As an example, when a team debated the possibility of comb-shaped buildings, the initial intention was to avoid long facades that would act as barriers with the surrounding neighbourhoods. By doing so, gables would be facing West and the main facade South. A second advantage was then identified with regards to integrating passive-design strategies. Consequently, some adjustments were made to the combs’ thickness in order to assure that each dwelling could be day-lit, cross-ventilated, and partly heated by the sun in the winter. This example illustrates the win-win, holistic nature of design solutions, and the practitioners’ overall holistic approach to the design problem. The latter seems rooted in a ‘global objective’ the designers appeared to have: improving the living context and the quality of the neighbourhood for its future inhabitants. On a more general level, often an underlying and often decisive argument for design choices (Gehl, 2010).

### **Discussion: A climate adaptation tool built on design practices**

The findings from the questionnaire and the workshops provide an outline of essential characteristics of the planned design-aid tool. First of all, the tool is modelled on the different phases of a typical design process: (1) Diagnostic, (2) Programming, and (3) Design. Its intended purpose is to support practitioners in designing climate adaptive projects, contributing to practitioners’ continued education by adapting to their ‘learning by doing’-

approach (i.e. through projects). Its use could enhance their understanding of how climate change will manifest in an urban context, and how their design can contribute to adaptation. Education also influences the practitioners' 'guiding principles' (Lawson, 1993). Composed of a practitioner's design principles, values, and beliefs, it is constructed throughout a professional career, and heavily influences design decisions. Therefore the proposed tool is will be a pedagogical tool, and could furthermore support e-learning and future training workshops. It will display different types of information to popularize scientific concepts. Moreover, Identifying urban and architectural precedents as well as relevant rules of thumb, is a promising way to facilitate integration of adaptive solutions into a design process. In this regard, the tool will also function as a adaptation-database, containing exemplary projects (e.g. eco-neighbourhoods), and concrete levers of action (e.g. "green roof", "albedo", "ecological corridor"). In a longer perspective, we imagine that the database could evolve with contributions from architects and urban planners to aid 'translating' the scientific knowledge to design practices.

Based on these main strategies, the prototype-tool is envisioned as an online application offering different levels of information regarding climate change adaptation. Over time it will offer an extensive database comprising exemplary urban and architectural precedents. This simple and solution-oriented information could be presented as: (A) Fact-sheets providing knowledge on environmental issues, and a questionnaire to guide an environmentally oriented site analysis; (B) "Solution sheets" providing in-depth information, including strengths and weaknesses of suggested solutions, and (C) "Project sheets" exhibiting detailed case studies. The following details the suggested approach for using the CapaCity-tool in a concrete design situation. Users can create an account to save their projects; an aid in constructing adaptation knowledge.

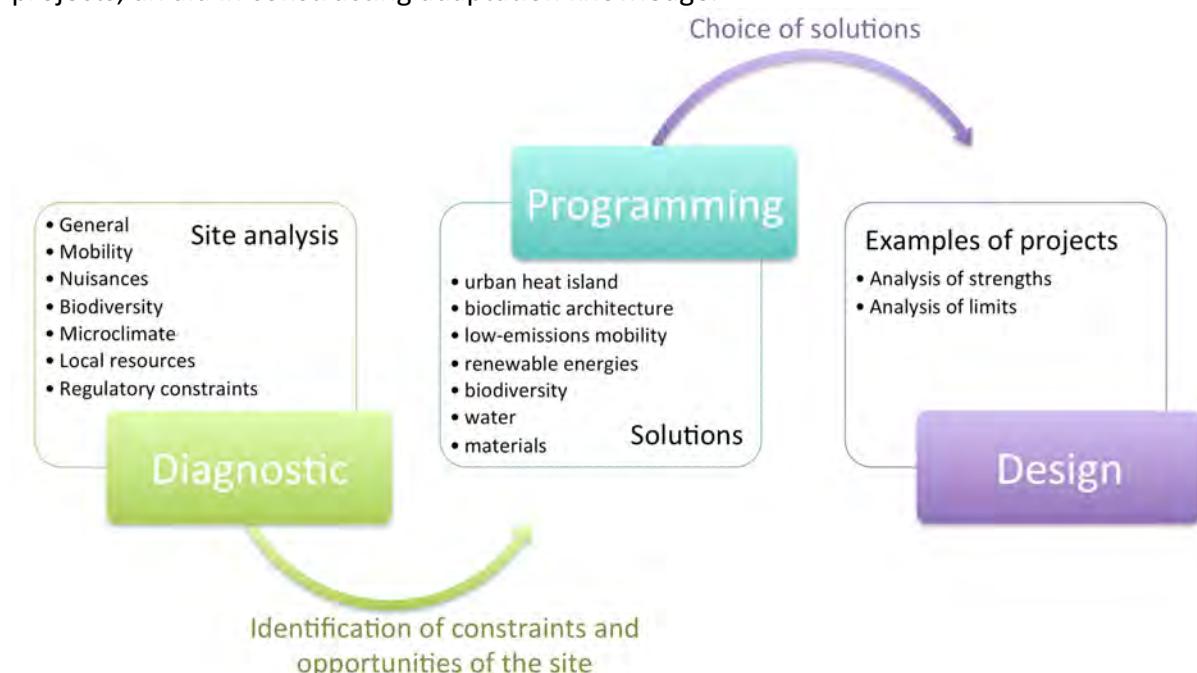


Figure 1. General structure of the CapaCity-tool

### **Component 1: Diagnostic**

In "Diagnostic" a first interface will allow the user to complete a questionnaire to conduct an environmentally-oriented site analysis in order to define an environmental

profile of a project. For each segment of the analysis, the user will be asked to answer a series of questions structured according to seven environmental themes. For the prototype these correspond to main adaptation challenges for the Toulouse-region. Each answer to the multiple-choice questions is associated with a coefficient. The sum of these provides an overall score for each of the seven environmental themes, thus defining a "proposed environmental profile". This profile will allow to identify adaptation constraints and opportunities of the site, and to select the main environmental themes to be treated in priority in the programming phase (see Table 1). Text, external links, and pictures accompany the questions, a means to enable the user to better understand an environmental theme, which data to be collected, and possible tools to deepen the environmental site analysis.

Environmental themes in the prototype tool						
Constraints due to the urban heat island	Opportunities to implement bioclimatic architecture	Opportunities to implement low-emissions mobility	Constraints to preserve biodiversity	Opportunities to implement renewable energies	Constraints due to water management on site	Opportunities to implement local materials

Table 1. The environmental themes the most important for climate adaptation in the Toulouse-region

At the end of the Diagnostic, the environmental profile of the project is displayed. The environmental themes will be ranked according to their scores into three categories: High Priority, Medium Priority, and Low Priority. The users will be able to modify this ranking, for instance according to particular client requirements, in order to define a final "environmental profile of the user" to be used in the "Programming".

### ***Programming***

For "Programming" the tool offers a series of "High Priority" environmental issues based on the profile. However, users can consult the totality of the database topics. Here the environmental issues of the tool will be presented as "Solution sheets", enabling the user to understand potential physical processes involved in the issues, and mechanisms that can be used to adapt a neighbourhood to climate change (e.g. "green roof", "albedo", "ecological corridor"). The user will be able to select "Solution sheets" in relation to the environmental profile of the project. When doing so, the tool will alert the user to possible interactions and interdependencies among the solutions that should be taken in to consideration.

### ***Design***

In "Design" exemplary projects where solutions selected in the previous steps are implemented are displayed. These will be exemplary urban projects, analysed as much with regards to their short-comings as to their strengths. In addition to the analysis (texts and pictures), these "Project sheets" will contain tags with a score between 0 and 3 to identify the implementation of different solutions. This allows assigning each project with a note corresponding to the suitability of the example project with the user's project and potential solutions selected in section 2. Projects with the highest scores will appear first in the list.

## **Conclusion**

The results of the first phase of the CapaCity-project drew attention to the need for research to gain a deeper understanding of designers' particular way of knowing and acting when tackling complex problems such as climate adaptation. Establishing a constructive dialogue between research and practice is necessary to better integrate expert knowledge in the design process. It could also provide researchers with a better vocabulary to translate climate change to the urban context. Due to the relatively small number of survey respondents and design workshops participants, the use of the reported results should be done with caution. However, they provide good indications of designers' needs and tendencies. The findings suggest that practitioners are concerned with climate-related issues. Their knowledge of solutions is rooted in their experience and education. Workshop participants extensively referred to urban and architectural precedents, as well as rules of thumbs, in order to develop their design schemes. At the opposite, they barely consulted any of the technical and technological resources available during the design game. Survey respondents reported to disregard tools they perceive as complex, time-consuming, costly, or that pose problems of incompatibility and interoperability. A determining influence of design constraints and guiding principles on a projects' resolution was also observed.

These results allowed identifying strategies to be implemented in the climate adaptation design-aid tool prototype, in order to meet the specific needs of urban designers and architects. The suggested tool reflects the solution-based design process, but also strive to be an educational tool. The application will guide the users following three stages of an urban project (diagnostic, programming and design), suggesting methods, solutions, and examples relevant to their specific projects. The tool is primarily intended for urban design and architecture professionals, but also for students in these fields. The tool is currently being finalized. The first component, "Diagnostic", was recently tested with a group of seven professionals and students within architecture, applying it for an environmental site analysis of a specific neighbourhood in Toulouse. All participants expressed an interest for this segment of the tool. They appreciated the design time saved with the "Diagnostic"-part, and the provided information about environmental site analyses.

The long-term goal of CapaCity is to develop a tool that is truly usable for urban practitioners, and supporting them in engaging further in climate adaptation. Thus strengthening a city's contribution to meeting the consequences of climate change.

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## **References**

- Augustin, S., Coleman, C., 2012. *The Designer's Guide to Doing Research: Applying Knowledge to Inform Design.* John Wiley & Sons.
- Bierbaum, R., Smith, J.B., Lee, A., Blair, M., Carter, L., Chapin, F.S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E., Verduzco, L., 2013. *Mitigation and Adaptation Strategies for Global Change* 18, 361–406.
- Cross, N., 2006. *Designerly ways of knowing.* Springer, London.

- Darke, J., 1979. *Design Studies* 1, 36–44.
- Dilling, L., Lemos, M.C., 2011. *Global Environmental Change* 21, 680–689.
- Dubois, C., 2014. Adapter les quartiers et les bâtiments au réchauffement climatique; une feuille de route pour accompagner les architectes et les designers urbains québécois. Université Laval et INSA de Toulouse, Québec, Canada.
- Dubois, C., Cloutier, G., Potvin, A., Adolphe, L., Joerin, F., 2015. *Frontiers of Architectural Research* 4, 1–11.
- Gehl, J., 2010. *Cities for people*. Island Press, Washington, DC.
- Gunawansa, A., Kua, H.W., 2014. *Sustainable Development* 22, 52–62.
- Harries, T., Penning-Rowsell, E., 2011. *Global Environmental Change* 21, 188–197.
- Horvat, M., Dubois, M.-C., Snow, M., Wall, M., 2011. International survey about digital tools used by architects for solar design ( No. T.41.B.2). International Energy Agency Solar Heating and Cooling Programme.
- Kirkeby, I.M., 2012. *Nordic Journal of Architecture Research* 24.
- Kleerekoper, L., Van Esch, M., Baldiri Salcedo, T., 2012. *Resources, Conservation and Recycling*. 64, 30–38.
- Lawson, B., 2006a. *How designers think: the design process demystified*, 4. ed. ed. Elsevier/Architectural Press, Amsterdam.
- Lawson, B., 2006b. *How designers think : the design process demystified*, 4th ed. ed. Architectural Press, Oxford.
- Lawson, B., 2007. *What designers know*. Elsevier/Architectural Press, Amsterdam.
- Lawson, B., 2013. Design and the Evidence, in: Procedia - Social and Behavioural Sciences. Presented at the "From Research to Practice". Asia Pacific International Conference on Environment-Behaviour Studies, University of Westminster, London, pp. 30–37.
- Lemos, M.C., Kirchhoff, C.J., Ramprasad, V., 2012. *Nature Climate Change* 2, 789–794.
- McAndrews, C., Deakin, E., Schipper, L., 2013. *Journal of Environmental Planning and Management* 56, 674–694.
- Rittel, H.W.J., Webber, M.M., 1973. *Policy Sci* 4, 155–169.
- Schön, D.A., 1983. *The reflective practitioner : how professionals think in action*. Basic Books, New York.
- Schön, D.A., 1988. *Design Studies* 9, 181–190.
- Shaw, R., Colley, M., Connell, R., 2007. How to implement adaptation through design and development., in: *Climate Change Adaptation by Design: A Guide for Sustainable Communities*. Town and Country Planning Association, London, pp. 16–47.
- Skogheim, R., 2008. Mellom kunsten og kundene Arkitekters yrkessosialisering og profesjonelle praksis (PhD-thesis). University of Oslo, Oslo.
- Smith, I., Williams, K., Hopkins, D., Joynt, J., Payne, C., Gupta, R., 2013. *Structural Survey* 31, 301–313.
- Tennøy, A., 2012. *How and Why Planners Make Plans, Which If Implemented, Cause Growth in Traffic Volumes*. Norwegian University of Life Sciences, Aas, Norway.
- de Wilde, P., Coley, D., 2012. *Building and Environment* 55, 1–7.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Spatial Analysis on Intra-Urban Temperature Variation under Extreme Hot Weather by Incorporating Urban Planning and Environmental Parameters: A pilot study from Hong Kong**

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**Abstract:** The number of extreme hot weather events have raised significantly in Hong Kong. Due to urban heat island effect, urban thermal environment of Hong Kong has been deteriorated. However, there is limited spatial understanding of intra-urban temperature variation under extreme hot weather conditions and climate-sensitive design for reducing heat load in severe heat events. Thus, there is a need to analyse the spatial distribution of intra-urban temperature variation of extreme hot weather and the impact of urban environment parameters on intra-urban temperature differences. In this paper, firstly, hourly air temperature records from 40 Hong Kong Observatory stations from 2011 to 2015 were collected to analysis hot night and very hot day. Secondly, for spatially mapping the very hot days and hot nights, kriging, a geostatistical interpolation algorithm, was adopted. Thirdly, urban environmental parameters (digital elevation model information, sky view factor and the NDVI) were incorporated in co-kriging interpolation for a more comprehensive understanding of the correlation of extreme hot weather and their spatial patterns. The generated maps of very hot day and hot night can provide better understanding of intra-urban temperature differences under extreme hot weather events and help to create climate-sensitive design strategies to cope with climate change locally.

**Keywords:** extreme hot weather, intra-urban temperature variation, climate-sensitive design, high density city, climate change

### **Introduction**

There is a growing number of heat waves since the end of the twentieth century and this growing trend will continue throughout the 21th century(IPCC, 2014). Hong Kong has more frequent extreme weather events such as very hot days and hot nights since its urbanization started in the 1960s(HKO, 2015). Urban thermal environment of Hong Kong has been deteriorated due to urban heat island effect. It's reported that Increase in 1 °C in hot days was associated with 6.82% increase in deaths in Hong Kong(Fung, 2004). As the number and duration of extreme heat events are likely to increase with climate change, it is important to obtain a more comprehensive understanding of extreme hot weather in urban environment. The conditions of extreme hot weather are generally based on the meteorological data acquired at ground-level meteorological stations(WMO& WHO, 2010). However, there is insufficient information on the spatial distribution of intra-urban temperature difference variations due to the limited coverage of the stations(WHO/Europe, 2004; WMO& WHO,

2010). Moreover, the problem is aggravated with the limited knowledge of the effect of urban environment on extreme hot weather and appropriate urban planning and design in the context of adapting and mitigating the extreme heat events. Therefore, there is an urgent need for better understanding of the spatial variation of extreme hot weather for more climate-responsive urban planning and design and hence more sustainable urban living.

This study aims to obtain a comprehensive understanding of spatial variation of intra-urban differences in temperature under extreme hot weather using spatial interpolation techniques. The understanding of the intra-urban temperature variation under extreme hot weather can help policy makers and urban planners to have a better understanding on the spatial distribution of the extreme hot weather, thus taking effective and targeted action for the most vulnerable areas. Also, the urban environment characteristics can contribute to the urban planning and building design for the resilience and adaption strategies of Hong Kong, therefore reducing the adverse impact of heatwaves at present and under climate change.

## **Materials and Methodology**

### ***Study Area***

Hong Kong ( $22^{\circ} 16' 50''$  N,  $114^{\circ} 10' 20''$  E), located on the southeast coast of China, has total area of about 1104 square kilometres covering Hong Kong Island, Kowloon and the New Territories and Islands. The terrain of Hong Kong is mountainous with steep slopes, where the elevation ranges from sea level to over 900m above sea level(Morton, 1995).

Hong Kong has monsoon-influenced subtropical climate, experiencing very hot weather in summer. Air temperatures typically reach  $33^{\circ}\text{C}$  on the hottest summer days, cooling to  $26^{\circ}\text{C}$  in urban and  $24^{\circ}\text{C}$  in rural areas at night(Nichol et al., 2012). On one hand, the temperature is continuously growing. The annual mean temperature increased  $0.12^{\circ}\text{C}$  per decade from 1885 to 2015 in average. The rate of increase in average temperature reached  $0.17^{\circ}\text{C}$  per decade during 1986-2015(HKO, 2015). On the other hand, there are more frequent occurrence of the extreme hot weather in Hong Kong. The annual count of hot nights and very hot days has increased significantly, by 19 and 10 respectively from 1885 to 2015(HKO, 2015). Moreover, extreme temperature in Hong Kong further suggests that the number of extreme hot weather is expected to increase significantly in the 21th century (HKO, 2015).

### ***Data***

Hourly air temperature data from 40 air temperature stations of the Hong Kong Observatory in June, July, and August (the months defined as summer in Hong Kong) were used for mapping out the intra-urban temperature variation under extreme hot weather. The 40 stations can represent both city and rural environments of Hong Kong (Figure 1). The years 2011-2015 were selected for this study because the past five years have more extreme hot records and most complete database of temperature recordings available for Hong Kong. And also this is a pilot study. Later the findings will be applied to a case study with a longer study period.

Based on the findings of Hong Kong Urban Climatic Map project, urban morphology parameters include digital elevation model (DEM) information, sky view factor (SVF) and the normalized difference vegetation index (NDVI) were selected to capture and describe urban geographical and morphological characteristic(Ng et al., 2015; Ng et al., 2012; Ren et al., 2011). The intra-urban distribution of the temperature excess is largely dependent on local surface characteristics and previous studies have identified a link between these parameters and air temperature(Unger, 2008). Air temperature generally decreases with elevation and air

temperature is often lower with higher altitude(HKO, 2017). SVF is important for the spatial variation of air temperature within the urban environment(Maru et al., 2015). Temperature studies in Hong Kong showed that places with higher greenery coverage often have lower maximum temperature than that with lower greenery coverage, in particular in summer(HKO, 2017).

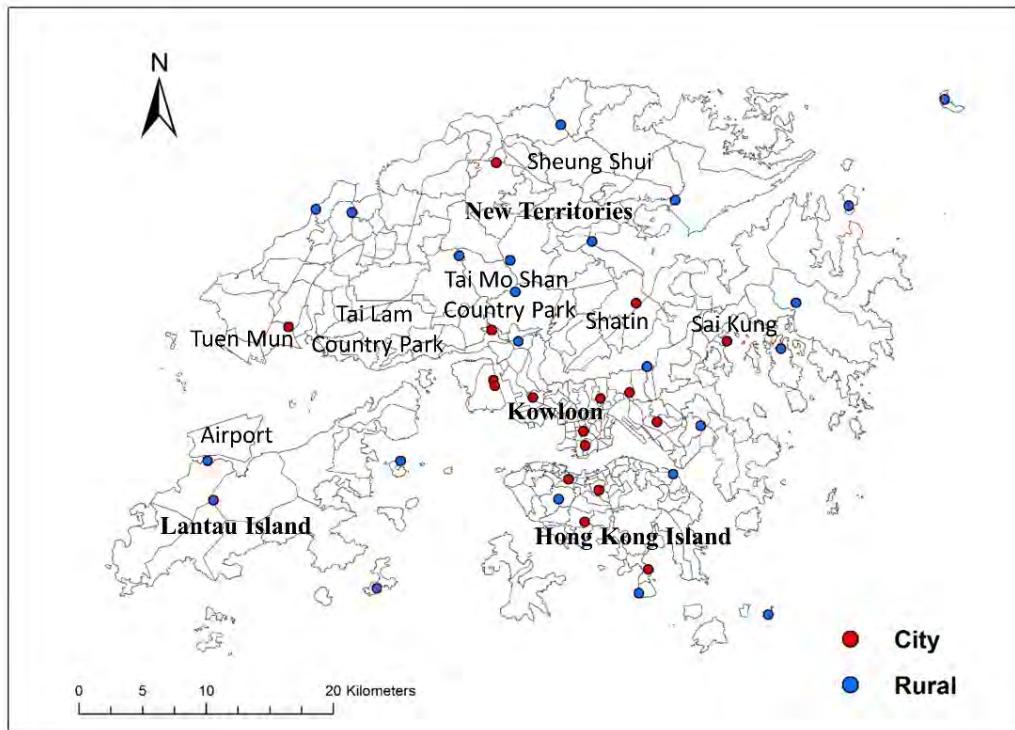


Figure 1. Distribution of the HKO stations.

Table 1. Urban Morphology Parameters.

parameter	resolution	year
SVF	1km	2009
DEM	1km	2009
NDVI	1km	2016

### Kriging Analysis

In order to represent different levels of extreme hot weather, temperature classes defined by HKO were used (HKO, 2015). The classes are defined as hot nights (days with a minimum temperature of 28°C or above) and very hot days (days with a maximum temperature of 33°C or above). However, the existing definition of extreme hot weather in Hong Kong is inadequate in days with many hot hours but the minimum temperature less than 28° C. It cannot be classified as a hot night according to the HKO definition but it may still have high potential of heat hazard. In order to represent the heat hazard in a more objective and comprehensive way, the cumulative hours above 28° C and 33°C thresholds are chosen as measure for hot nights and very hot day.

First, the annual mean hot night hours and very hot day hours of each station over the ten years were counted based on the observatory data. The selected hazard measures at each site were plotted as point values in GIS. Second, a geostatistical interpolation algorithm, called kriging, was applied to map the very hot days and hot nights. The kriging interpolation

expresses the spatial variation of the property in terms of the variogram, and minimizes the prediction errors which are themselves estimated(Oliver, 1990).

In addition, urban morphology parameters such as the SVF, NDVI and DEM also have influence on the spatial pattern of extreme hot weather. These factors were also involved in the interpolation process by co-kriging to gain a more comprehensive understanding of the correlation of hot weather and spatial patterns.

## **Result and Analysis**

### ***Very Hot Day and Hot Night between City and Rural Stations***

According to the statistical results of the extreme hot weather under city and rural stations, it can be observed that city stations have higher mean, median very hot day hours and hot night hours than rural stations, indicating significant urban heat island (UHI) effect in Hong Kong and urban areas are more vulnerable to heat hazards(Landsberg, 1981; Oke, 1982, 2002). In addition, hot night hours have larger range and values than very hot day hours thus there are more extreme heat events during night time.

Table 2. Statistical results of the extreme hot weather between city and rural stations.

Hot weather indicator	City station	Rural station
Average very hot day hours	62.4	49.5
Median very hot day hours	48.1	37
Range of very hot day hours	11-190.6	0-149.8
Average hot night hours	527.8	223.8
Median hot night hours	533.6	202.8
Range of hot night hours	113.6-693.6	0-485

### ***Spatial distribution of very hot day***

The spatial distribution of the very hot days and hot nights was mapped and the potentially hot areas in Hong Kong identified by using kriging and co-kriging method (Figure 2&3). The most frequent very hot day hours occur in the north of the New Territories where most are rural areas according to the kriging mapping results. The number of very hot days is predominantly high in rural areas due to the more open settings without high-rise buildings or high mountains where there is better air ventilation and less sky obstruction, leading to persistently high temperature. More frequent very hot day hours are also identified in urban areas in Kowloon and the western Hong Kong Island. There are few very hot day hours in Lantau Island, Tai Mo Shan Country Park and the rest of the Hong Kong Island.

The DEM information helps differentiating very hot day hours in the mountainous areas such as Lantau Island, Hong Kong Island and Tai Mo Shan Country Park. The mapping results are similar with the kriging mapping result after incorporating NDVI and SVF. However, more very hot day hours are detected in the west of the New Territories with relatively little vegetation coverage.

The results delineate more detailed spatial distribution of the extreme heat events after incorporating all the three urban environmental factors in the interpolation process. The high frequency of very hot day hours in the northern New Territories are more scattered than that of the original kriging mapping. Also, very hot day hours are also detected in Shatin, airport in the Lantau Island, which is not represented by the previous results. In addition, very hot day hours in Tai Lam Country Park are characterized as low by taking elevation into account.

In particular, the lowest very hot day hours are located in the peak of the Tai Mo Shan Country Park which is the highest place in Hong Kong.

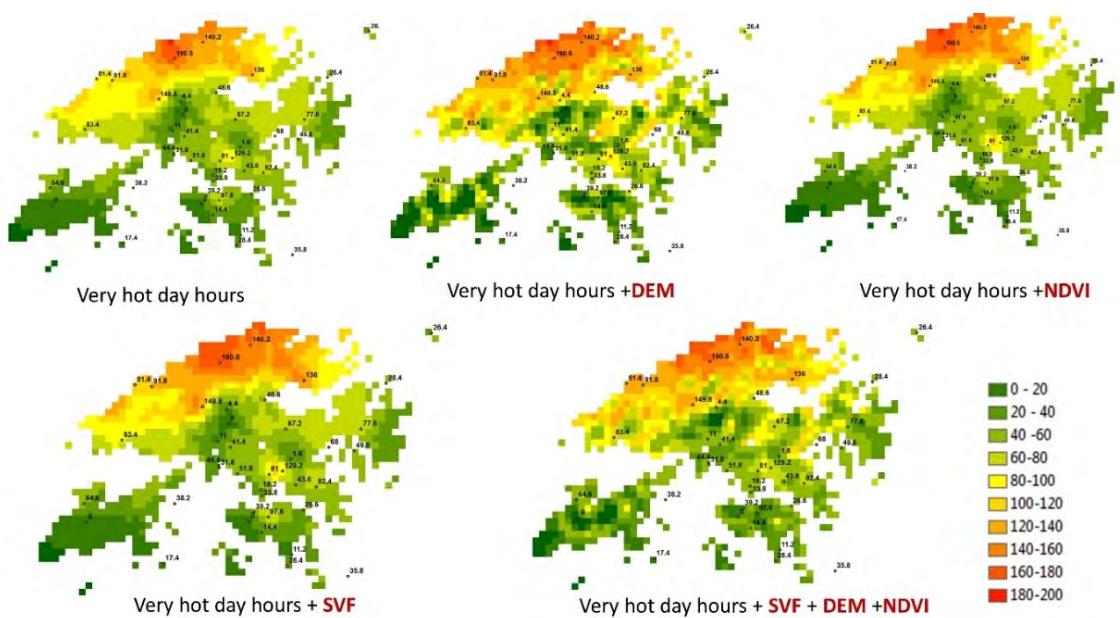


Figure 2. Mapping results of annual average very hot day hours (2011-2015).

### ***Spatial distribution of hot night hours***

High hot night hours occur most frequently in urban areas such as Kowloon and Hong Kong Island while low hot night hours are located in the rural areas in Hong Kong. Dense development with tall buildings can affect the solar radiation, reduce wind speed and slow down night time cooling rate in the urban area, leading to generally higher night time temperature in urban areas when compared with rural stations(HKO, 2010). Also, the counts of hot nights are much greater than that of very hot day which indicates that night time extreme heat events are more frequent and severe than daytime extreme heat events.

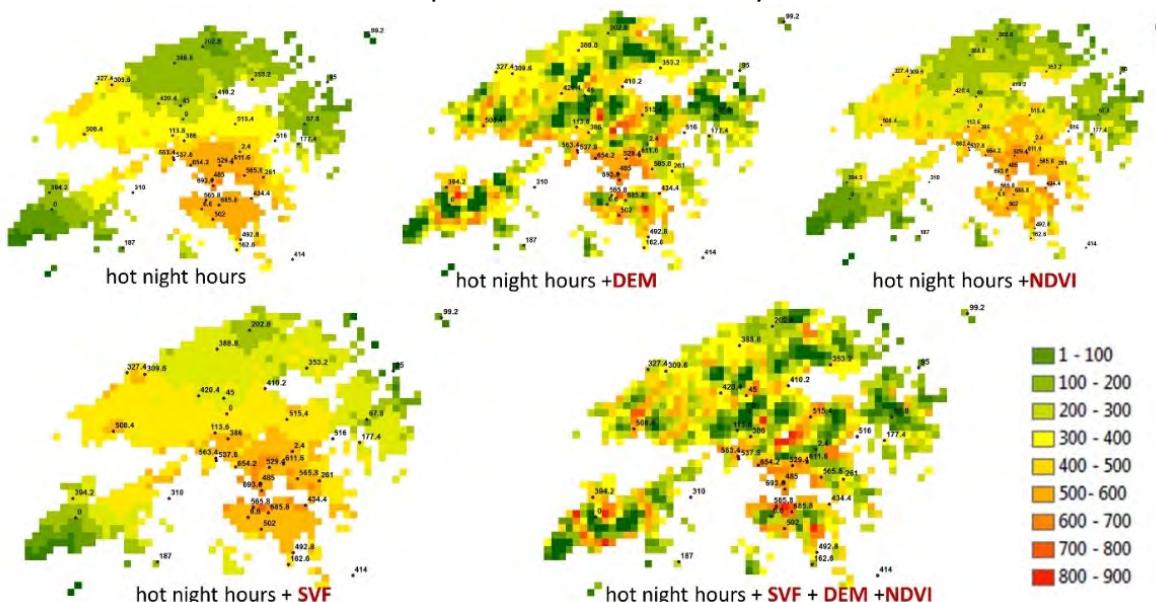


Figure 3. Mapping results of annual average hot night hours (2011-2015).

The range of hot night hours has been significantly increased after co-kriging using DEM information. Lowest values of very hot day hours have been detected in high-altitude locations such as Lantau Island and Tai Mo Shan Country Park due to their high environmental lapse rate. NDVI helps characterize hot night hour variation more detailed according to different greenery coverage. SVF increased the value of hot night hours in the whole New Territories in comparison with the original kriging mapping. Larger areas in urban areas such as Kowloon, Hong Kong Island and Shatin district are characterized as high very hot day hours by taking the three parameters into account. The co-kriging method also captured hot night hours in the west of the New Territories. The result is similar with the co-kriging mapping using DEM, demonstrating that DEM may have dominant impact on the spatial distribution of the extreme heat events in comparison of the other two parameters.

## **Conclusion**

This study mapped the intra-urban temperature variation under extreme hot weather by incorporating DEM, SVF and NDVI based on the annual average very hot day hours and hot night hours from 40 weather stations in Hong Kong. It's found that urban stations have more frequent extreme hot weather than rural areas, indicating significant UHI effect in Hong Kong. In addition, there are more extreme heat events during night time in Hong Kong. Moreover, the north of the New Territories has more daytime extreme hot weather while urban areas in Kowloon and Hong Kong Island have more extreme heat events during night time. Finally, the co-kriging mapping incorporating all the three parameters delineates the spatial distribution of the intra-urban temperature under extreme hot weather in a more detailed and reasonable way.

Findings of the present paper contribute to a better understanding of the spatial variation of extreme hot weather in high-density urban environment. It also provides local-scale information for the selection of representative meteorological stations for heat wave warning system which the World Meteorological Organization and the World Health Organization jointly call for actions by the governments.

In future, we will interpolate average, minimum and maximum air temperature to further analyse the spatial pattern of extreme hot weather and map hourly average air temperature to understand the temporal variations of extreme heat events. We also plan to determine a more appropriate heatwave threshold, to select alternative index for the kriging interpolation (Glenn et al., 2017) and as well as to link the mapping result with heat-related mortality in Hong Kong for future enhancement of local heat health risk studies, thus ensuring a healthy urban living for local citizens.

## **Acknowledgement**

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## Reference

- Fung, W. Y., Lam Ka Se, Hung Wing Tat. (2004). Provision of Service for Characterizing the Climate Change Impact in Hong Kong. Hong Kong: The Hong Kong Polytechnic University.
- Glenn, M., Angie, B., & Florian, P. (2017). Meteorological risk: extreme temperatures. In P. Karmen, M. F. Montserrat, D. G. Tom & C. Ian (Eds.), *Science for disaster risk management 2017: knowing better and losing less* (pp. 257-270). Publications Office of the European Union, Luxembourg.
- HKO. (2010). Warm nights Retrieved 26th November, 2010, from <http://www.weather.gov.hk/blog/en/archives/00000076.htm>
- HKO. (2015). Climate Change Pamphlet - Hong Kong in a Warming World. In H. K. Observatory (Ed.), *Hong Kong Observatory*. Hong Kong.
- HKO. (2017). Spatial temperature variations in Hong Kong Retrieved 23rd January 2017, from <http://www.hko.gov.hk/blog/en/archives/00000209.htm>
- IPCC. (2014). *Climate change 2014: impacts, adaptation, and vulnerability*. New York, NY, USA: Cambridge University Press, Cambridge, United Kingdom.
- Landsberg, H. E. (1981). *The urban climate* (Vol. 28): Academic press.
- Maru, R., & Ahmad, S. (2015). The Relationship between Temperature Patterns and Urban Morphometry in the Jakarta City, Indonesia. *Asian Journal of Atmospheric Environment*, 9(2), 128-136. doi: 10.5572/ajae.2015.9.2.128
- Morton, B. H., Elizabeth. (1995). *An Introduction to the Cape d'Aguilar Marine Reserve, Hong Kong*. Hong Kong: Hong Kong University Press.
- Ng, E., & Ren, C. (2015). *The urban climatic map: a methodology for sustainable urban planning*: Routledge.
- Ng, E., Ren, C., & Katzschnner, L. (2012). Urban Climatic Mapping in Hong Kong. *Journal of Heat Island Institute International* 7(2), 55-64.
- Nichol, J. E., & To, P. H. (2012). Temporal characteristics of thermal satellite images for urban heat stress and heat island mapping. *ISPRS Journal of Photogrammetry and Remote Sensing*, 74, 153-162. doi: 10.1016/j.isprsjprs.2012.09.007
- Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1-24.
- Oke, T. R. (2002). *Boundary layer climates*: Routledge.
- Oliver, M. A., and Richard Webster. (1990). Kriging: a method of interpolation for geographical information systems. *International Journal of Geographical Information System*, 4(3), 313-332.
- Ren, C., Ng, E., & Katzschnner, L. (2011). Urban climatic map studies: a review. *International Journal of Climatology*, 31(15), 2213-2233. doi: 10.1002/joc.2237
- Unger, J. (2008). Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *International Journal of Environment and Pollution*, 36(1-3), 59-80.
- WHO/Europe. (2004). Heat waves: risks and responses *Health and Global Environmental Change*: Regional Office for Europe.
- WMO& WHO. (2010). Heat waves and health: guidance on warning system development. In G. McGregor, Pierre Bessemoulin, K. Ebi, and Bettina Menne (Ed.), *World Meteorological Organization-No. 1142*: WMO& WHO.



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## Green Roofs in Cuban Housing. Types, Evaluation and Proposals

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**Abstract:** Green roofs are a good alternative to mitigate and to revert climate change, reducing heat island effect and improving urban resilience. However, green roofs are traditional in vernacular cool weather architecture, but not in warm humid regions. Cubans aborigines' architecture and communities were made of natural (dry) fibers, with low heat transmittance, and very permeable to wind, and even, colonial Mediterranean architecture and urbanism were not characterized by the presence of green roofs. Green roofs arrived in Cuba with modern architecture during the second half of the 20th Century, following one of the five principles: The roof garden. Nevertheless, they proliferated from the 90's, as a result to the economic crisis, as a way to provide food in urban agriculture. Taking into account these antecedents, the paper presents the results of a research work focused on evaluating several of possible alternatives of green roofs for Cuban housing, in order to propose recommendations for their use, taking into account a cost – benefit analysis. Results show that the three studied green roof types are feasible to be used in Cuban housing, what is not only possible, but convenient, since their benefits, including the reduction of maintenance costs, compensate the slight execution extra-costs.

**Keywords:** Green Roof, Housing, Cost-benefit analysis, Warm – humid climates, Cuba.

### Introduction

Green roofs importance is increasing because of their contribution to reduce global warming and to reverse climate change, since they absorb CO<sub>2</sub> and produce O<sub>2</sub>. They also diminish the effect of the heat urban island and partially retain rainwater, decreasing the flooding risk.

However, green roofs are not traditional in Cuba, despite some existing examples in good conditions while buildings are near the end of their useful life. On the other hand, as part of the urban agriculture experience, people themselves have created ways to plant in yards, terraces and roofs by different modalities.

Because of that, it is possible to think that green roofs may constitute a viable alternative to be applied in Cuba, but other classifications should be proposed to include local Cuban experiences, and their climatic behavior in warm and humid climate have to be verified. Green roof types appropriate to housing in Cuban conditions are evaluated in the present paper.

### Materials and Methods

The research has been carried out in three steps, and diverse particular methods have been used in each of them. In the first step, information was collected, processed and discussed in order to identify variables, parameters and indicators as basis for classification and evaluation

of green roofs. Historic – logic method was also used to evaluate the evolution of the study object.

Second step is referred to green roofs in Cuba, in which theoretical research methods were also used, complemented by empirical ones, such as field work, observation, measurement, calculation and design. For that, green roof identified in Havana were visited, and experts in urban agriculture were interviewed. From the collected information, three theoretical green roof models were designed, in order to quantify their indicators to be compared to a conventional roof.

In the third step, the impact of some green roof types on the interior thermal environment was verified by an experimental research in which temperature and humidity in real cases were measured. All the collected and calculated data were integrated in a cost – benefit analysis of green roofs in Cuba, based on a qualitative – quantitative – comparative evaluation, to get to conclusions respect to the more appropriate solutions.

### **Green Roofs. Theoretical Framework**

Planting vegetation directly over the building roofs is a common practice since ancient times (Vijayaraghavan, 2016). Continue use in roofs of soil and vegetation since ancestral times, mainly in cool weather, is also recognized (Minke, 2004), in order to get thermal isolation by thermal mass (soil and vegetation) avoiding heat lost during winter.

According to Minke (2004, pp.7), in cool climates, green roofs “heat”, since they storage heat from indoor environments, and in hot climates, they “cool” since they keep indoor spaces isolated from exterior high temperatures. For him, vegetation and soil use to moderate temperature variations, and gained heat is not only storage but absorbed.

During the first half of the twenty century, with the so called “five points of the modern architecture”, the aesthetic intention of green roof is reinforced. According to Vijayaraghavan (2016), the current trend of green roofs started in Germany during the 60's. From the late twenty century, and as result of the ecological crisis, they were considered as a good way to recover the green lost as a consequence of the construction.

### ***Basis for the Cost – Benefit Analysis***

Among the more common benefit of green roofs considered in the cost – benefit analysis, is the absorption of CO<sub>2</sub> and pollution reduction by vegetation, (Borzog Chenani et al., 2015), which depends on vegetation type, roof orientation and wind behavior (Vijayaraghavan, 2016), as well as reduction of air temperature near to the roof, which may reach 1°C at night in Singapore, when the intensity of the heat urban island is higher (Li y Norford, 2016).

Another advantage reported by green roofs is noise isolation, depending on the substrate composition and thickness, as well as vegetation type and density (Connelly M y Hodgson M, 2015). However, this benefit is not significant for housing in Cuba, because of the need of permeable spaces for ventilation that make difficult to avoid noise penetration. They also have a great capacity to retain part of the rain water, diminishing flooding risk.

Food production is a benefit not related by the international literature about green roofs, probably because it is not possible in extensive solutions that are more frequent at global scale. However, productive function has been essential in contemporary Cuban green roofs, but in other different types.

Besides that, green roofs preserve impermeable layer systems from mechanical damages or chemical decomposition or biological processes, and improve their durability,

avoiding their exposition to temperature changes. On the other hand, a roof garden offers a good protection against fire (Minke, 2004).

Each green roof, despite the type, generates additional costs respect to a conventional one, due to the structural over load, needed execution materials or components, and required maintenance during the exploitation step. Costs depend on technology and roof type, but also on the location.

Maintenance of green roof doesn't need investment or specialized labor, so, it doesn't generate additional costs. Ecological solutions with permaculture techniques (Cruz, Sánchez and Cabrera, 2006) may use rainwater supplied by gravity and organic fertilizers, without additional costs. Then, it is possible to consider null maintenance costs in green roofs, with additional benefits respect to the conventional ones, increasing durability of impermeable systems (Pérez González and González Couret, 2016).

### ***Influence on Thermal Indoor Environment***

Respect to the favorable influence on indoor thermal environment under the green roof, results of a study carried out by Yang et al (2015) for a sub-tropical climate in China, evidenced an energy reduction of 4 kWh and 5 kWh per day in rooms with extensive green roof and substrate thickness of 20 cm and 10 cm respectively, related to an exposed roof. Razzaghmanesh et al (2016) said that Green roofs reduce temperature during day, but they may increase it by night, because of the thermal lag, which is not desirable in warm – humid climates as Cuban one, where temperatures are high during day and night.

On the other hand, Nichau et al., cited by Li and Norford (2016), demonstrated that the thermal isolation effect of a Green roof in winter is more significant than the cooling effect due to the water evaporation during summer. For those authors, a worrying respect to using vegetation above roofs in humid tropical zones is related to the increment of relative humidity, affecting the thermo-physiologic human comfort. In the same way, Razzaghmanesh et al. (2016), affirm that reducing temperature by vegetation is less effective when relative humidity is high.

Taking into account the exposed arguments, it is possible to conclude that green roofs are more effective to isolate interior spaces from outdoors in cool regions, while they may not be so effective to cool in warm climates, mainly, when relative humidity is high. Because of that, Vijayaraghavan (2016) recognize that thermal benefits of green roofs continue under discussion. However, it is referred to green directly related to roof, but Cuban repertory shows the existence of other modalities not considered by the international literature, where vegetation is not directly in contact to the roof, and then there is no thermal inertia but shading.

### **Green Roofs in Cuba**

Green roofs have never been a tradition in Cuba, since in the Cuban warm and humid climate thermal mass is not convenient. On the contrary, roofs should not store heat during day to be transmitted to indoors at night, when temperatures are high, for what shading or double roofs, preferably ventilated with low absorptivity external surfaces are required (González Couret, 2010).

Aborigine architecture before colonization was built by natural dry fibers, low transmittance and inertia, which envelope didn't heat and housing was permeable and ventilated. On the contrary, urban architecture later developed by the Spanish colonizers, followed the Mediterranean model: common thick walls, relative small windows and

courtyard. Differently from the original referential architecture in the dry Mediterranean climate, courtyard in the colonial Cuban architecture is full of vegetation in the warm – humid climate (González Couret, 2010). Then, in colonial cities, vegetation don't appear on the streets or roofs, but in yards.

In some over wall urbanizations as El Vedado, common walls and courtyard were lost, and vegetation appeared on gardens and streets, but normally not in roofs (González Couret, 2010). According to the research carried out, the first green roofs found in Havana correspond to the period of modern architecture of the 50's, and then, it is associated to the roof garden promoted by Le Corbusier and his five points. In a general way, these roofs could be seen from surrounding high buildings, and then, their function were more aesthetical than thermal or productive. Detected examples con intensive or extensive green roofs.

A continuity of this tradition is observed in some buildings during the early 60's. However, when these examples are referred as important exponents of modern architecture, green roofs are not mentioned (Rodriguez 2011). During the 70's, green roofs are not associate to urban buildings but to great city parks, which intention was integration to nature.

The presence of vegetation in roofs reappear in Cuba during the 90's, but because of different reasons and with other modalities. As a consequence of the necessity to produce food at the local scale generated by the economic crisis and supported by the Urban Agriculture Movement, diverse new modalities of green roofs in housing have been developed, simple and easy to execute.

Despite people also execute green roof with the substrate directly related to the roof, mainly to produce food, in a general way, there are solutions developed by self-construction (Sánchez Medina, s/f), which, on the contrary of the already mentioned, vegetation is separated from the roof, in containers or as a double roof. Those are increasing in Cuba, popularized with additional objectives, such as shading, ventilation and structural cooling to diminish indoor high temperatures during day and night during the whole year. It is due to their simplicity and economy.

### **Proposed Classification**

According to international literature, Green roofs are composed by a system of elements conforming horizontal layers installed directly over the building roofs, which could be classified as intensive and extensive (Borzog Chenani, 2015) (Connelly and Hodgson, 2015) (Li and Norford, 2016) (Minke, 2004) (Razzaghmanesh et al. 2016) (Vijayaraghavan, 2016) (Yang et al. 2015).

Independently of that, the study of Cuban repertory demands a new classification. A possible way of classification could be according to the main function. However, the most important proposal is based on the relationship between the substrate and the roof: separate or integrated (extensive or intensive). When vegetation is not directly related to the roof surface, it is in containers or planted on the ground, forming a double roof above.

### **Thermal Behaviour**

The influence of green roofs on indoor environment is an important benefit to be considered, but there have not been found precedent researches allowing to precise their impact in a warm and humid climate as Cuban one. Because of that and taking into account the possible influence of green roofs in energy and exploitation costs during the building useful life, an experimental research was carried out to measure air temperature in real case study.

For that, two green roofs types were selected: separated (double roofs) and integrated (extensive). Measurements were also taken in a common roof finished by ceramic tiles and exposed to direct solar radiation.

#### ***Case Study: Exposed Roof and Green Double Roof***

To develop the experiment, two bathrooms were taken as case study, located in housing buildings in the same block and with similar orientation, separated approximately 50 Km in New Vedado. The selected spaces have the same dimensions, windows area and function (bathroom). Roof is made of concrete 16 – 19 cm width and finished by with ceramic tiles.

Measurements were taken by data loggers HOBO locates 1m below the roof, simultaneously to other equipment located outdoors inside a wooden and ventilated cabin, protected from sun by vegetation, programmed to register values each one hour, during three days in August, 2016.

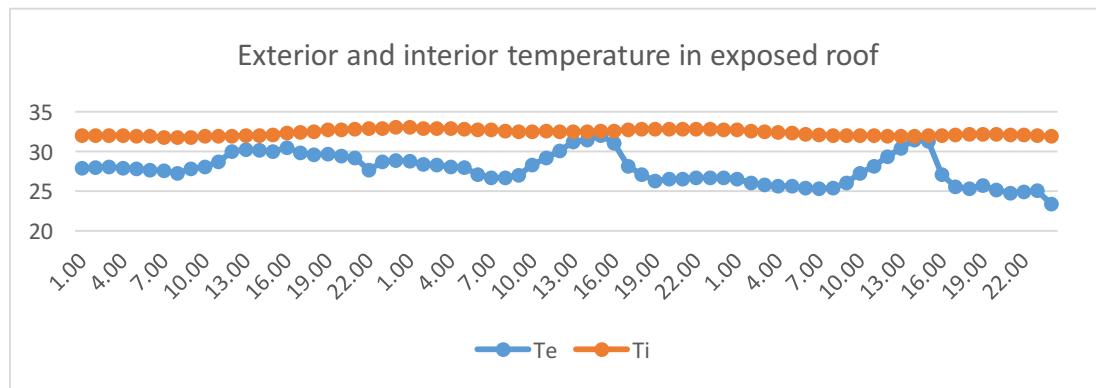


Figure 1: Indoor and outdoor temperature under the exposed roof.

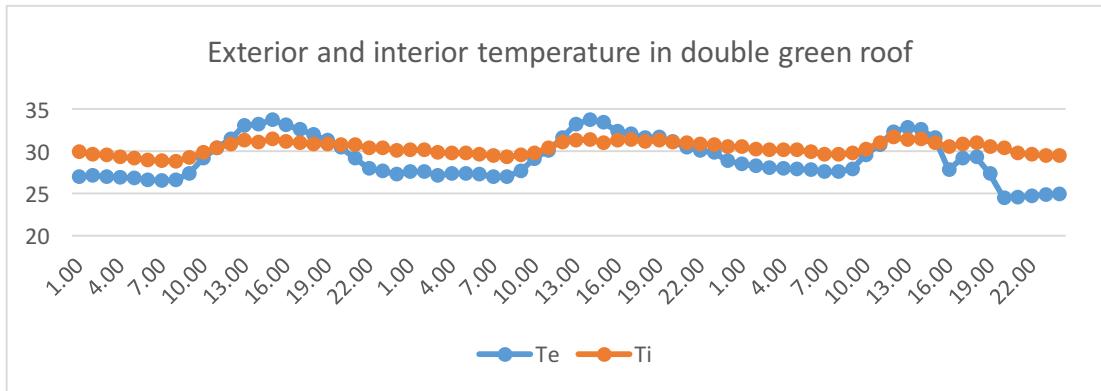


Figure 2: Indoor and outdoor temperature under the double green roof.

The interior space below green roof kept always cooler respect to outdoors (Figure 1) than the one below the exposed roof, with differences up to over 6°C (Figure 2). Major temperature differences are produced during afternoon and night, when families stay at home and people are sleeping. It demonstrate the thermal advantages of this type of green roof in the warm and humid Cuban climatic conditions.

#### ***Case Study: Extensive Green Roof***

It was very difficult to find an extensive green roof to make the experiment, because they are scarce, located far from the city, sometimes abandoned, and even some of them are being deconstructing. It was possible to coordinate to carry out measurements in a

bathroom of a Pavilion in the National Botanic Garden, half undergrounded, with an extensive green roof partially shaded by surrounded trees.

Measurements were made a similar way than the former cases, placing the data logger 1m below the roof, and taking data simultaneously to another equipment located inside a wooden and ventilated cabin under a tree, programmed to measure each 1 hour during 3 days in October 2016. However, they were rainy days with constant outdoor temperatures below 25°C and high relative humidity (between 75% and 98%). Nevertheless, high inertia in this green roof types is demonstrate, despite the additional effect of being half undergrounded (Figure 3).

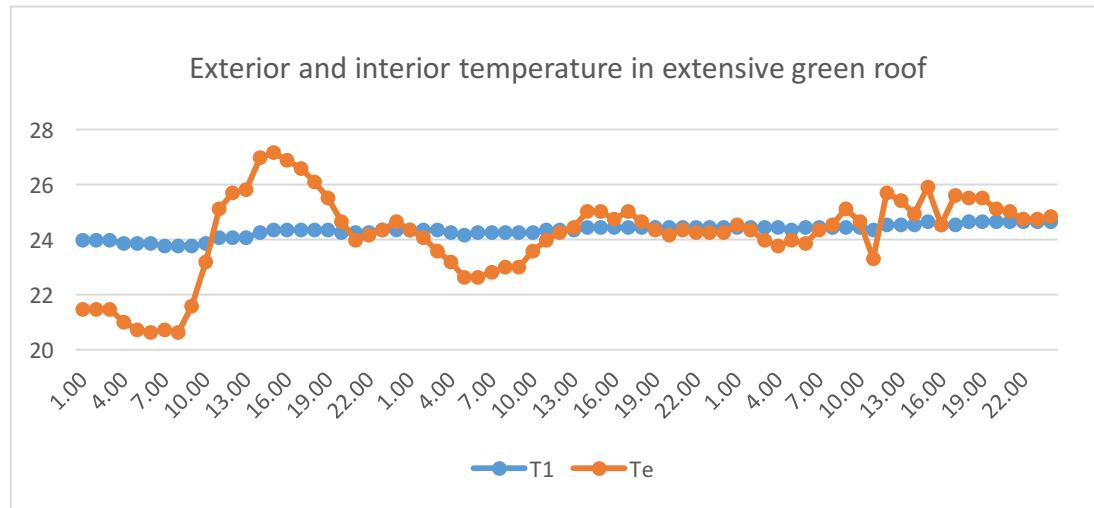


Figure 3: Indoor and outdoor temperature under the extensive green roof.

### Thermal Comfort Evaluation

Both green roofs are more favorable than the exposed roofs. However, the extensive one shows a higher thermal inertia provoking a difference of more than 2°C to outdoors at night respect to the one with double roof, but in the afternoon there is a contrary effect (Figure 4).

By plotting the combination of the extreme temperature and relative humidity conditions indoors in the Givoni's Bioclimatic Chart (Givoni, 1998), it is possible to observe that indoor environmental conditions under the exposed roof are out of the comfort zone, including the one in which is possible to improve them by ventilation. However, in the space under the green double roof (measured during the same season), thermal conditions are better, being even possible to achieve comfort by ventilation (Figure 5).

On the other hand, indoor environment under the extensive green roof in the Botanical Garden, measured during rainy days in October, shows more favorable temperatures, being possible to achieve comfort even without ventilation, despite the high relative humidity.

### Cost – Benefit Analysis

Benefits of each of the selected green roof types have been estimated based on information from international literature and national experts. They have been evaluated in a qualitative way based on quantifying the needed resources, taking into account the generic theoretical models elaborated. A double green roof costs \$3.75 extra per m<sup>2</sup> respect to a common roof, while an extensive one requires an additional investment of \$18.00 per m<sup>2</sup>, which means more than a double of the exposed roof cost. However, integral qualitative evaluation indicates that benefits compensate extra costs, despite extensive roof is the most

expensive. Then, results show that the three studied green roof types are feasible to be used in Cuban housing, what is not only possible, but convenient (Pérez González y González Courret, 2016).

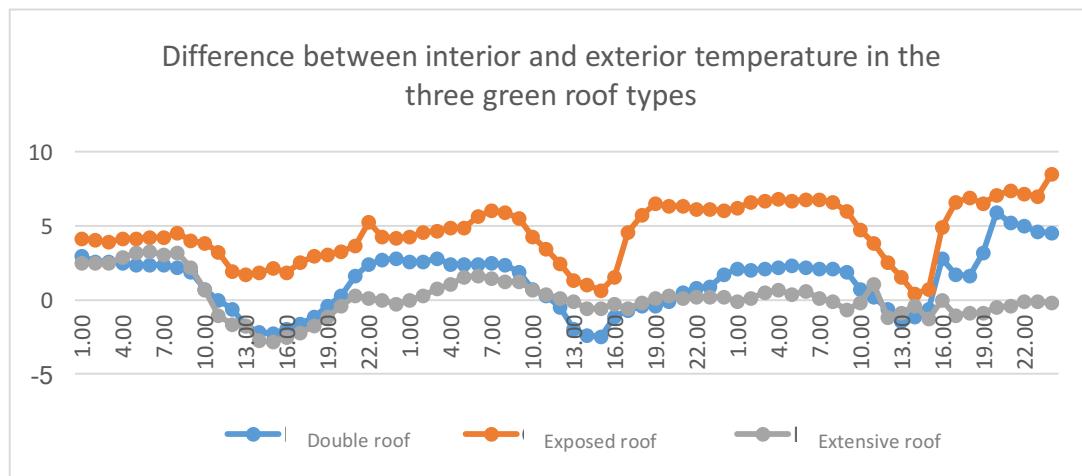


Figure 4: Difference between indoor and outdoor temperature in the three green roof type studied

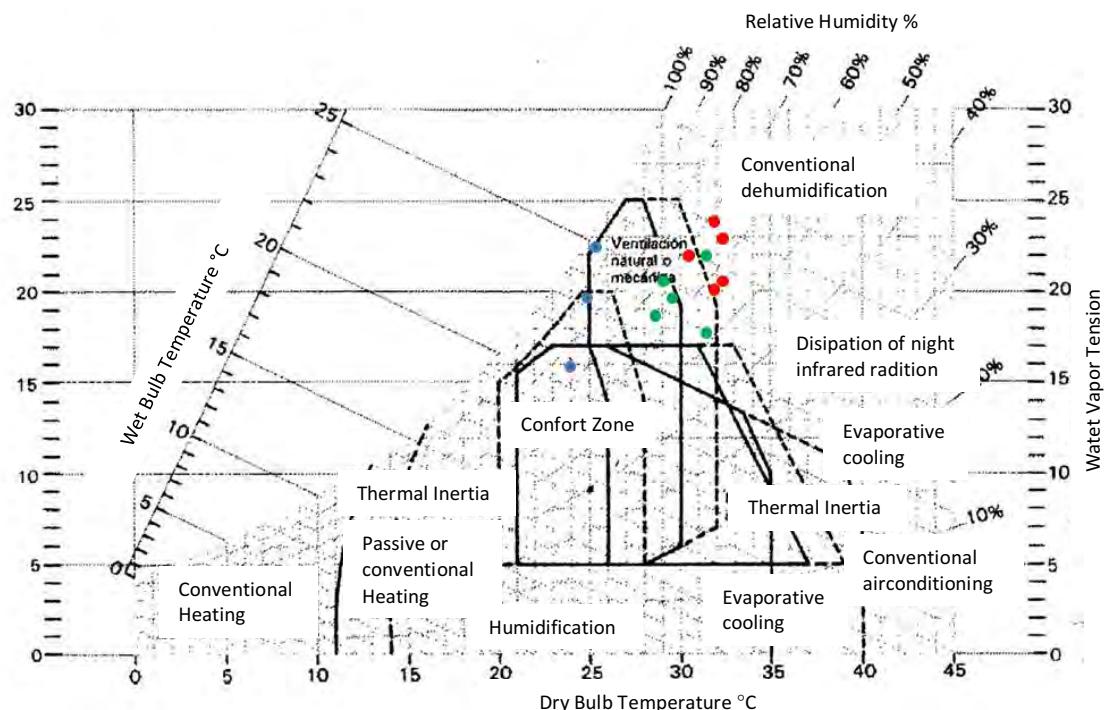


Figure 5: Combination of maximum and minimum values of temperature and relative humidity measured under the three green roof type studied, in the Givoni's Bioclimatic Chart. Exposed roof; RED; double green roof; GREEN; extensive green roof; BLUE

Some recommendations have been finally offered to use each type. Integrated green roofs (extensive) should be considered since the design step and included in the construction process. It is not recommended their further addition or being used in popular self-constructed housing. However, separated green roofs may be developed later on by people progressive actions, taking into account offered recommendations (Pérez González y González Courret, 2016).

## **Conclusions**

Green roofs are not a tradición in Cuba. They started in the 50's as part of aesthetic explorations in modern architecture, their development continues during the 60's, and they were reborn in the 90's with a productive objective, generating simple and economic popular solutions.

From the international literature and the Cuban repertory, a new classification have been proposed according to the relationship between the substrate and the roof: Integrated (intensive and extensive), and Separate (containers and double roof).

According to measurements carried out, interior spaces under double green roof present lower temperatures in up to 6°C respect to those under a roof exposed to solar radiation. Higher differences occur during night, coinciding to the mayor housing occupation. Extensive green roofs also offer favorable conditions, but with mayor thermal inertia.

The cost – benefit analysis demonstrate that any of the studied green roofs favour comfort indoors, complemented by natural ventilation.

## **Acknowledgments**

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## **References**

- Connelly, M; Hodgson, M (2015). Experimental investigation of the sound absorption characteristics of vegetated roofs. *Building and Environment*, 92, pp. 334 – 346.
- Cruz, M.C.; Sanchez, R., Y Cabrera, C. *Permacultura criolla*. Bogotá Linotipia Bolívar y CIA.
- Bozorg Chenani, Sanaz; Lehvavirta, Susanna; Hakkinen, Tarja (2015). Life cycle assessment of layers of Green roofs. *Journal of Cleaner Productions*, 90, pp. 153 – 162.
- Givoni, B. (1998). *Climate considerations in building and urban design*. New York; International Thompson Publishing.
- González Couret, Dania (2010). *Arquitectura bioclimática*. Havana: Félix Varela.
- Rodriguez, Eduardo Luis (2011). *La arquitectura del movimiento moderno. Selección de obras del Registro Nacional*. Havana: Ediciones Unión
- Li, X-X; Norford, Leslie (2016). Evaluation of a cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore. *Urban Climate*, <http://dx.doi.org/10.1016/j.uclim.2015.12.002>
- Minke, Gernot 2004. *Techos verdes. Planificación, ejecución, consejos prácticos*. Montevideo: Fin de Siglo, Montevideo.
- Pérez González, Luis Guillermo; Gómez, Dania. Techos verdes apropiados para viviendas en La Habana. In: *Cuarto congreso internacional sobre medio ambiente construido y desarrollo sustentable (MACDES 2016)* Habana, November 25 – 28. CIIA, CUJAE.
- Razzaghmanesh, Mostafa; Beecham, Simon; Salemi, Telma. The role of Green roofs in mitigating Urban Heat Island effects in the metropolitan área of Adeleide, South Australia. *Urban Forestry and Urgan Greening*, 15, pp. 89 – 102.
- Sánchez Medina, Roberto (no date). *Experiencias de permacultura en azoteas y terrazas cubanas: Contribución al desarrollo local sostenible*. Havana: Fundación Antonio Núñez Jiménez.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The 'Second Skin' and Thermal Adaptation In Changing Climate

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**Abstract:** In order to determine the extent to which clothing, the 'second skin', can affects the thermal perception of building space occupants, this paper analysed the results of field studies conducted in the hot humid climate of Nigeria. Using a mixed-mode methods; climate measurements during two different climate seasons (dry and rainy seasons) were taken, also 450 subjective questionnaires were administered to participants, and a number of observational studies were also recorded. The results showed that of all the thermal variables measured and recorded during the field survey, clothing insulation had the strongest correlations to the thermal sensation of participants. The correlation coefficient of clothing insulation was 0.516; whereas indoor air temperature was 0.236, outdoor air temperature had a correction coefficient of 0.131, relative humidity, 0.115 and metabolic rate was 0.020. Thus, in hotter climate, the 'second skin' has a major role to play in enabling building occupants to better adjust to their thermal environment, with a reduced reliance on mechanical forms of ventilation, which are expensive to run and maintain. The paper concludes by recommending policy measures office managers/management can implement to ensure office workers have appropriate clothing to ensure thermal comfort in a changing climate.

**Keywords:** Adaptation, clothing, hot humid climate, 'second skin', thermal perception

### Introduction

Climate change is a global issue that affects all parts of the planet. It is a burning subject among scientist, economist, politicians, professionals in different fields including the construction and the built environment. The impact of the global warming is felt on a local scale also. In a quest to save our planet from impact of this change, the United Nations has been at the forefront of many initiatives that have been taken in this regard.

Some of the key international initiatives that have been spearheaded in response to the climate change issue, according to the United Nations Framework Convention on Climate Change (UNFCCC), have highlighted *mitigation* and *adaptation* as the main objective of the United Nations in combating climate change . **Mitigation** approach involves human intervention to reduce the sources of greenhouse gases, the major cause of global warming (IPCC, 2014a). **Adaptation** is the process of adjusting to the effects of actual or expected climatic condition. In human systems, adaptation attempts to moderate, avoid or take advantage of beneficial opportunities. In some natural systems, the intervention of humans may speed up the adjustment process (IPCC, 2014b).

As a step in the right direction, the adaptive thermal comfort has been widely recognised as an innovative approach to achieve energy efficient and sustainable building designs, in response to climate change. The adaptive principle (Nicol and Humphreys, 1973) indicates that one of the major actions usually taken by subjects in order to adapt or adjust

to any change in environmental conditions and in restoring comfort is clothing adjustment. Clothing, regarded as the ‘second skin’, allows us to adapt to the thermal conditions in our immediate surrounding. It also affects our perception of the thermal environment. However, in the emerging world; office workers are often required to wear official clothing or uniforms by their employers (Efeoma, 2016). The military and the paramilitary, wear uniforms, as do officials of state parastatals and other organisations. In private companies, employers have dress code policy for all staff, which is expected to promote the company’s corporate image. Workers, in these situations, have little or no control over their choice of clothing. Hence, such dress code or uniform policies usually restrict the ability of workers to adapt to the thermal conditions surrounding their work environment.

Hence, this paper is concerned with examining the adaptation aspect of the UNFCCC’s objective in combating climate change in relation to the built environment in the hot humid climate. The main objective is to investigate the relationship between clothing insulation and thermal perception of local office workers in the hot-humid climate of Enugu, Nigeria; in comparison with other thermal variables.

### **Practical Case Studies of Clothing Adaptation**

There are few contemporary case studies or reports on practical case studies related to clothing adaptation. The following two cases cited below are based on the campaign carried out by the Japanese Ministry of Environment. They were termed: *Cool Biz* campaign in 2005 and *Super Cool Biz* campaign in 2011.

#### **A. Japanese *Cool Biz* Campaign**

During the summer of 2005, the Japanese Ministry of the Environment began a campaign that is termed: *Cool Biz* campaign (Japanese Ministry of Environment, 2005). During the *Cool Biz* campaign, office workers in government ministries were expected to adopt a certain dress code. The *Cool Biz* dress code advises workers to wear short-sleeved shirts without ties or jackets. They were also expected to starch collars of their shirts to stand up and to wear trousers made from materials that breathe and absorb moisture. The purpose of this campaign, according to the Ministry of the Environment, is to reduce energy consumption by limiting the use of air conditioning. Hence, in all central government ministries the temperatures of air conditioners were set at 28°C until the end of the summer.

At the end of the summer, the Ministry conducted a web-based questionnaire survey on the *Cool Biz* campaign (Japanese Ministry of Environment, 2005). Of the 1,200 men and women randomly selected for the survey, 95.8% of the respondents agreed that they knew about *Cool Biz* campaign. Based on the survey conducted, the Ministry estimated that the campaign resulted in a reduction in CO<sub>2</sub> emission that is equivalent the volume of CO<sub>2</sub> emitted by about 1 million households for one month.

#### **B. Japanese *Super Cool Biz* Campaign**

Following the great east Japan earthquake of March 11, 2011, the shutdown of many nuclear power plants for safety reasons led to energy shortage, which forced the Japanese government to mandate a 15% peak power reduction to address shortage in summer (Tanabe et al., 2012). The government recommended that the temperature of air conditioners should be set at 28°C. The *Super Cool Biz* campaign was then launched to encourage workers to wear clothing appropriate for the office summer heat. Polo shirts and trainers were allowed in government office. Under certain circumstances, workers were also

allowed to wear jeans and sandals. During the summer of 2012, the *Super Cool Biz* campaign was repeated in Japan.

While the *Super Cool Biz* campaign was a good strategy for saving energy, it however affected workers productivity. According to the result of field studies conducted by Tanabe et al, the self-estimated productivity in 2011 summer was 6.6% lower than that of the previous summer (Tanabe et al., 2012).

The Japanese *Cool Biz* and *Super Cool Biz* campaigns, highlighted the extent to which clothing (the second skin) can affects both the adaptation and perception of office workers to the thermal conditions surrounding their work environment. They also showed that there is need to investigate good strategies of electricity savings that would not affect workers thermal comfort and productivity.

## Methodology

The research for this study was conducted in Enugu, a city in the hot humid climate zone of Nigeria. It is located at an altitude of approximately 223m above sea level and it lies between latitudes 5°55'15"N and 7°6'36"N, and longitudes 6°55'39"E and 7°54'26"E. It has an undulating topography with scattered hills and knolls, with approximate land area of about 7,161km<sup>2</sup> (Efeoma, 2016).

Being in tropical Nigeria, Enugu is hot all year round with a mean daily temperature of 26.7°C (Sanni et al., 2007). The climate of Enugu is humid and the peak of the humidity is experienced between March and November (Reifsnyder et al., 1989). As with the West African geographical land mass, Enugu experiences two major seasons, the rainy and dry seasons. During the dry season months of December and January, the city is also affected by the '*Harmattan*', a dust-laden trade wind from the Sahara desert, usually occurring over two to three week period, which can also affect visibility.

The data for this study were obtained from office workers and office spaces in the complexes of the Federal Radio Corporation of Nigeria (FRCN) and the Federal Road Safety Corps (FRSC), Enugu. The surveys were conducted during the dry and rainy seasons in 2014. In order to determine the wide range of environmental conditions that office workers in the climate zone can adapt to, surveys were carried out in office spaces that were both naturally ventilated and others which had mixed-mode<sup>1</sup> ventilation in place. Also, spaces included open plan (OP) offices and enclosed space (ES) offices.

Throughout the period of the survey conducted during from January to March 2014 (dry season), and in the months of May to June 2014 (rainy season), dataloggers were placed in all the office spaces surveyed to record indoor operative temperature and humidity at 15 minute intervals. The dataloggers were located within 1 meter of each participants' workstation to record the actual thermal conditions being experienced by participants during normal working hours. Dataloggers were also placed outside the buildings to simultaneously record the corresponding air temperature and humidity of the immediate outdoor environment at the same time intervals as the indoor dataloggers. A Hand-held instrument was used to measure the air speed in the different spaces surveyed at different instances during the study period.

The questionnaires used for this study were administered in two parts. Part One of the questionnaire was used for the recruitment of participants on a voluntary basis. Paper

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<sup>1</sup> Mixed-mode ventilation in this research refers to office spaces that utilises a combination of natural ventilation from operable windows and some form of air-conditioning cooling system

copies of the first part of the questionnaires were distributed to a self-selected group of participants, who were office workers in both offices of FRCN and FRSC. For the purpose of anonymity, codes were assigned to each participants that completed the first part of the questionnaires. Part One of the questionnaire was only administered during the first stage of the field research, since the information collected from that part of the questionnaire remained unchanged throughout the course of the survey.

Part Two of the questionnaire was administered in both stages of the survey using a longitudinal approach (Efeoma and Uduku, 2016). For each day of the survey, three thermal comfort questionnaires were administered to each participant; one in the morning (before 11am), another one at mid-day (between 11am and 1pm), and the last one in the afternoon (after 1pm). This process was repeated for different days throughout the period of the two stages of the survey. Subjective thermal variables collected included: participants' subjective thermal comfort votes (COMF), thermal sensation (TSENS) and thermal preference (TPREF).

## Analysis of Results

### **A. Thermal Variables Measured and Recorded**

The thermal variables measured and recorded during the period of the survey included; indoor air temperature (TA\_In), outdoor air temperature (TA\_Out), indoor relative humidity (RH), metabolic rate (MET) and clothing insulation (CLO). The results are summarised in Table 1. As shown, there is less disparity in both indoor and outdoor air temperature measured during the period of the survey. With a coefficient of variation of 32.8%, clothing insulation has the most disparity of all the thermal variables measured and recorded.

Table 1: Summary of Thermal Variables Measured and Recorded

	TA_Out (°C)	TA_In (°C)	RH (%)	MET	CLO
<b>Maximum</b>	39.8	32.4	83.7	2.0	1.14
<b>Minimum</b>	24.4	24.4	40.2	1.0	0.51
<b>Mean</b>	33.3	28.5	59.5	1.14	0.73
<b>Std Deviation</b>	3.19	1.75	11.69	0.149	0.24
<b>Coefficient of Variation (%)</b>	9.6	6.1	19.6	13.0	32.8

In order to determine the subjective thermal sensation (TSENS) of the participants, the questionnaire adopted the ASHRAE seven-point thermal sensation scale (-3=Cold, -2=Cool, -1=Slightly cool, 0=Neutral, 1=Slightly warm, 2=Warm, 3=Hot). Participants were allowed to select all the options that apply and the resulting mean from options selected was used to determine the participants vote. The mean TSENS vote for all participants in the survey was slightly below "Neutral", between "Slightly cool" and "Neutral" with a value of -0.08. As shown in Figure 1, the breakdown of the mean TSENS votes according to office clothing policy indicates that with a median vote of 2.0 on the ASHRAE thermal sensation scale; participants in offices with strict clothing policy voted that they were much warmer compared to the group mean TSENS vote. While those of offices with flexible clothing policy are much more comparable to the group mean TSENS vote.

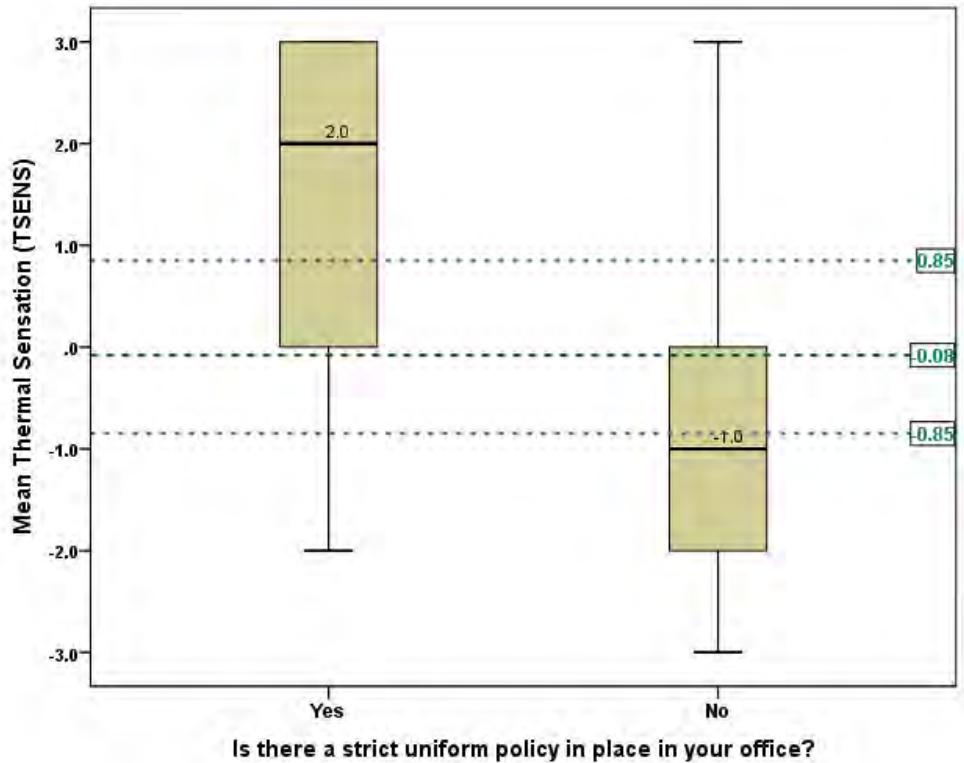


Figure 1: Distribution of mean TSENS according to office clothing policy

### **B. Correlation of Thermal Sensation to Other Variable**

Figure 2 shows the correlation matrix of the mean thermal sensation (TSENS) to the following variables: indoor air temperature, clothing insulation, outdoor air temperature, relative humidity and average metabolic rate. The bivariate scatter plots and the fitted lines are shown on both the left and right parts; Pearson's correlation values, their significance values and the corresponding R<sup>2</sup> values are shown on both the upper and lower part. The results show that thermal sensation is strongly correlated to clothing insulation ( $r=0.516$ ) and operative temperature ( $r=0.236$ ). It is also slightly correlated with outdoor air temperature ( $r=0.131$ ) and relative humidity ( $r=0.115$ ). It has a weak correlation to metabolic rate ( $r=0.020$ ).

The 2-tailed correlation is significant at the 0.01 level for clothing insulation, operative temperature and outdoor air temperature. While the correlation between the mean thermal sensation and relative humidity is significant at the 0.05 level. With a correlation significant of 0.678, there is no statistical significant correlation between mean thermal sensation and metabolic rate. This implies that, changes in the activities of participants of the survey did not affect their thermal sensation.

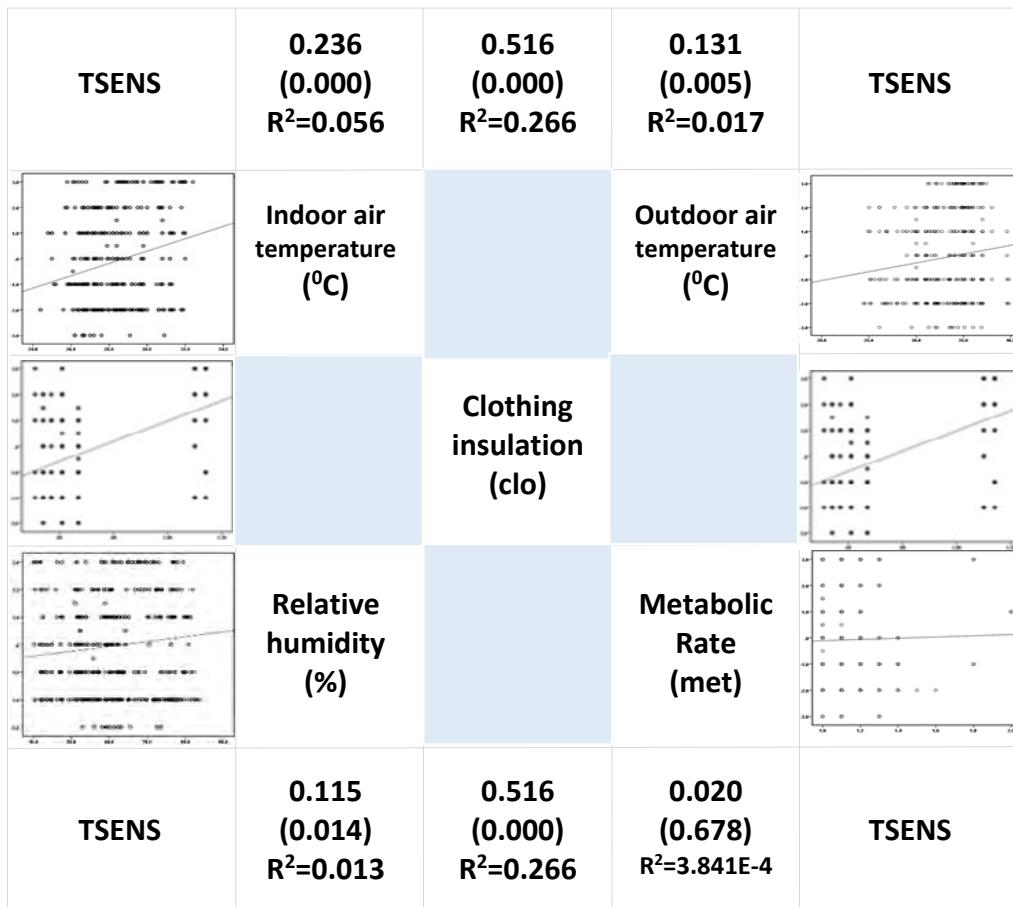


Figure 2: Correlation matrix showing the relationship between the mean thermal sensation (TSENS) and the following variables: indoor air temperature, clothing insulation, outdoor air temperature, relative humidity and metabolic rate. Bivariate scatter plots and the fitted lines are shown in both the left and right parts; Pearson's correlation values, their significance values and the corresponding  $R^2$  values are shown in both the upper and lower parts

### C. Relationship between clothing insulation and subjective thermal sensation (TSENS)

A regression analysis was also carried out to establish the relationship between clothing insulation and the subjective thermal sensation (TSENS) of the local office workers in the hot-humid climate of Enugu. Using the SPSS software, a linear regression analysis on the TSENS was carried out with respect to clothing insulation. The result of the relationship is summarised in Table 2.

The linear regression equation for the relationship between the participants' clothing insulation and the subjective TSENS votes is  $Y = 3.960*X - 2.961$  with a correlation coefficient of 0.521 and a p-value that is statistically significant at 0.01. This yielded a subject clothing insulation comfort range (TSENS between -0.85 and +0.85) of between 0.53 clo and 0.96 clo. This is in compliance with the adaptive comfort standard of ASHRAE Standard 55-2013, which specifies a clothing insulation range of 0.5 to 1.0 clo (ASHRAE, 2013).

Table 2: Summary of thermal sensation votes responding on clothing insulation

Sample	Comfort Range	Regression Equation	Pearson	P-value
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size (n)	-0.85≤TSENS≤+0.85 (clo)		correlations	
450	0.53 – 0.96	Y = 3.960*X-2.961	0.521	0.000

## Discussion

As shown in Figure 2, the R square value for the mean TSENS votes against clothing insulation of participants was 0.266. While this shows that the regression equation, in Table 2, could only explains 26.6% of the relationship, it is however statistically significant. Again, the low value of R square for the relationship explains how difficult it is to estimate human perception or psychology using statistical methods alone.

However, when this relationship is compared with the relationship between indoor TA\_In and TSENS, it could be seen that clothing insulation is a better predictor of the TSENS of participants than the indoor air temperature. This result is also supported by the analysis result illustrated in the correlation matrix; which shows that of all the thermal variables measured or recorded, CLO has the strongest correlation to TSENS. This strong correlation between CLO and TSENS thus shows that clothing was the major determinant of how participants perceived their thermal environment during the period of the survey.

This clearly shows that for building occupants to be comfortable within the ASHRAE adaptive comfort limits, office workers in the hot humid region should be given the opportunity to adjust their clothing within the range of 0.53 and 0.96 clo as established from this study. Strict uniform policies that specify office clothing with CLO value higher than 1, with no opportunity for workers to make adjustment, will make it difficult for the adaptive comfort of ASHRAE Standard 55-2013 to be apply in such office spaces where they occupied.

## Conclusion and Recommendation

This study has shown that there is a strong relationship between building occupants CLO and their TSENS. The relationship has also yielded a clothing insulation range of 0.53 and 0.96 clo. Hence, for adaptive comfort standard to be applicable in the hot humid climate zone of Nigeria, building occupants must be able to adjust their clothing within this CLO range. Above all, employers need to know what CLO values are and should be able to determine the CLO value of any office clothing ensemble they want to recommend to their staff.

Conceptually, the findings from this study will provide policy makers and employers with strict uniform or office clothing policy in Nigeria, and by extension the emerging world, a basis to review their current office clothing policy to a more flexible clothing policy that will encourage adaptive opportunities for workers to adjust their office clothing where necessary. This in turn will reduce reliance on mechanical cooling systems which are expensive to install and maintain.

In order to help the public and employers to understand what clothing is most appropriate to achieve thermal comfort in the local context; there is need for future research to look into the possibility of re-calibrating and publicising the clothing insulation scale as this research has shown that clothing was the most significant factor influencing thermal adaptation in the cases studied.

## References

- ASHRAE, 2013. ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy, ANSI/ASHRAE Standard 55. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.
- Efeoma, M.O., 2016. The Influence of Clothing on Adaptive Thermal Comfort: A Study of the Thermal Comfort of Office Workers in Hot Humid Conditions in Enugu, Nigeria (PhD Thesis). University of Edinburgh, United Kingdom.
- Efeoma, M.O., Uduku, O., 2016. Longitudinal Survey of Adaptive Thermal Comfort of Office Workers in the Hot Humid Climate Zone of Enugu, Nigeria, in: Proceedings of 9th Windsor Conference: Making Comfort Relevant. Presented at the Network for Comfort and Energy Use in Buildings, NCEUB, Cumberland Lodge, Windsor, United Kingdom.
- IPCC, 2014a. Climate Change 2014: Mitigation of Climate Change, Summary for Policymakers. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability, Summary for Policymakers. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Japanese Ministry of Environment, M.O.E., 2005. Cool Biz Campaign (published in Japanese language).
- Nicol, F.J., Humphreys, M.A., 1973. Thermal Comfort as Part of a Self-Regulating System. *Build. Res. Pract.* 1, 174–179.
- Reifsnyder, William, E., Darnhofer, T., 1989. Meteorology and agroforestry, in: International Council for Research in Agroforestry. Presented at the International workshop on the application of meteorology to agroforestry systems planning and management, International Council for Research in Agroforestry, Nairobi, Kenya.
- Sanni, L., Ezedinma, C., Okechukwu, R.U., Lemchi, J., Ogbe, F., Akoroda, M., Okoro, E., Maziya-Dixon, B., Ilona, P., Dixon, A.G.O., 2007. Cassava Post-Harvest Needs Assessment Survey in Nigeria: A Synthesis Report. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.
- Tanabe, S.-I., Iwahashi, Y., Tsushima, S., 2012. Thermal Comfort and Productivity in Offices under Mandatory Electricity Savings after Great East Japan Earthquake. Presented at the The Changing Context of Comfort in an Unpredictable World, London: Network for Comfort and Energy Use in Buildings.



# PLEA 2017 EDINBURGH

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## Resilient Urban Edges: Adaptive and Mitigative Design in Chennai

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**Abstract:** This paper investigates design responses to El Nino-mediated climatic disturbances, using the December 2015 Chennai floods as a test case. The effects of such disturbances are exacerbated by human intervention: urbanisation-led impermeabilisation of soil accentuates the urban heat island, makes water percolation difficult, increasing surface run-off. Using literature, precedents and on-site interviews with residents of a tenement block in severely-flooded Chennai, downstream of the River Adyar, key issues were identified. Additionally, impact of existing morphology on comfort conditions were derived using analytical tools of Envimet, Ladybug and CFD (outdoor) and TAS (indoor). The conclusions informed testing of hypotheses which merged with informal recycling practices of the residents. The paper discusses strategies employing recycled and local materials to build permeable surfaces (water-air-ground interfaces) to be embedded into existing architectural objects (by retrofitting), or utilised to build new experimental floating structures complementing the existing. The design studies show how strategies bring extreme temperatures of 42°C within a comfortable range in indoor and outdoor spaces; whilst contributing to flood mitigation. The paper speculates upon a resilient live-work environment for 2050 employing productive self-build networks to alleviate socio-economic polarisation characterising riverfronts, contributing to urban permeability and responding adaptively to daily, seasonal and extreme events.

**Keywords:** Chennai, El Nino, adaptive, mitigative, permeable

### Introduction

The El Nino is associated with temperature differences in the east-central Equatorial Pacific caused by trade winds moving towards South America instead Asia, resulting in weak monsoons in Asia. In India, particularly in urban areas like Chennai (fig 1), El Nino-mediated climatic disturbances manifests itself as dual conditions of droughts and floods. The drought scenario is exacerbated by the Urban Heat Island (UHI) effect (Amirtham, 2016) resulting in extreme temperatures and water and food shortages, while floods are made worse due to construction on the flood plains and unplanned rapid urbanisation. The effects of unplanned concretisation of the city are found in the existence of the UHI indicating an intensity of 2.48°C and 3.35°C during summer and winter respectively (fig 3). Rapid urbanisation (fig 2) has resulted in vegetative areas declining from 70% to 48% (1991-2012) in the metropolitan area, with built areas increasing from 1.46% to 18.5% and projected to be 36% in 2026 (Ramachandra et al, 2016). Further, India's population is estimated to increase four-fold by 2050, with new populations living in urban areas, 60% of which are not yet built (McKinsey, 2015). The city is unable to satisfy the needs of its 12 million, creating a paradox of an increasingly polarised thirsty metropolis, expanding onto flood plains of rivers of the city.



Figure 1. Location

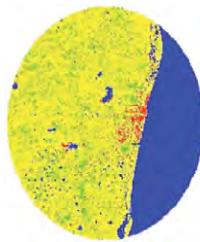


Figure 2. Growth from 2000, 2010 to 2026

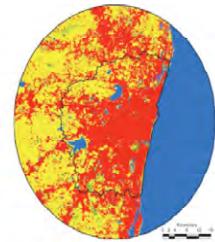


Figure 3. Heat Islands

### ***Area of focus – River and tenement settlements***

The area of focus is the river Adyar (fig 1), which burst its banks following the release of water from the Chembarakkam lake due to 539mm of rainfall on one day in December (which is the average rainfall for the month). The 12.2015 flood (fig 4,5a) turned the roads into water canals which perforated the urban fabric. The site chosen is a tenement settlement in Kotturpuram, which is on the curvilinear flood plain of the river and was inundated causing destruction to life and property - residents had to move to the terrace or be evacuated by boat. Chennai has a large number of such blanket developments built through a government housing scheme on low lying land unfavoured by real estate with informal settlements located around them. These blocks are generic in organisation with no attempt to engage with the informal lifestyle of its occupants. Therefore, the aim of this paper is to formulate design proposals that would allow for adaptation and mitigation of extreme weather events and typical conditions whilst engaging the city and local communities.



Figure 4. Before and after the flood

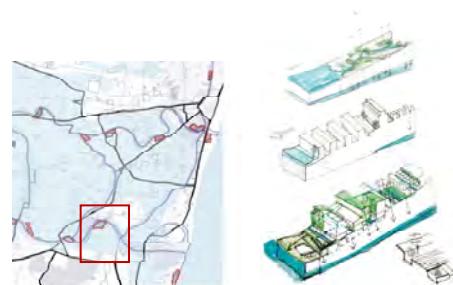


Figure 5. a) Site and b) hypotheses

### ***Hypotheses***

**Hypothesis 1 - Mitigative strategy:** What proposals can be introduced in the urban fabric to address El Nino-mediated extreme climatic events? The hypothesis is that layers of permeable surfaces, derived from the recycling economy and introduced in the fabric, will rethink landscape in cities, mitigate the heat island effect and provide ownership to the locals. This mitigative strategy explores permeability by using vegetation, water and synthetic materials in different ways in the urban and architectural fabric.

**Hypothesis 2 - Adaptive strategy:** What proposals can be introduced in the building fabric to address temperatures that are out of comfort for 95% of the year? The hypothesis is that layers of transition spaces, buffers and screens will aid in achieving outdoor and indoor temperatures within the comfort band throughout the year. This hypothesis is a design intervention where existing street typologies and unit typologies were tested, evaluated, redesigned and later applied to new typologies on the site.

Hypothesis 3 - Participative strategy: How can a riverfront be utilised to integrate the city and promote ecological awareness? The hypothesis is that a river can be more than just a connection point from A to B but also: a mobility infrastructure, a productive channel, a public realm and a climate mediator. As a participative strategy, this is an urban design place making strategy that investigates integrating the neglected rivers and its polarised edges with the rest of the city (fig 5b).

### Climate

Located at 13.0827° N 80.2707°E, Chennai has a tropical wet and dry/savanna climate (Köppen-Geiger classification: Aw) with a maximum air temperature between 41°C in the month of May and 20°C in the month of December. The climate variations from the IPCC A1B scenario for 2050 (fig 6) that were considered are an increase in temperatures (1-2°C) and out of comfort temperatures for 90% of the time, an increasing trend in rainfall in the monsoon season from October-December, increase in the global horizontal radiation annually (2716 hours of sunshine per year) and capitalisation on sea breeze from the East.

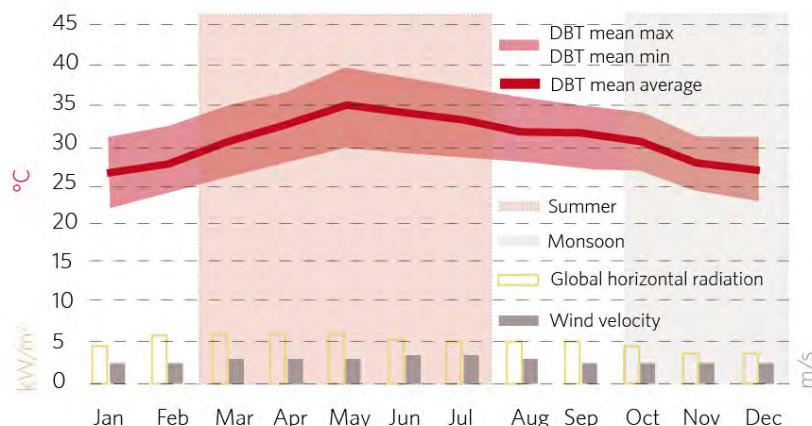


Figure 6. Monthly Average Climate Parameters - IPCC (2050) showing a rise in temperatures by 2°C

### Scope of work

The site consists of primarily 80 blocks within an area of 84,430 sqm. The orientation of the blocks (fig 7) (32x8x12m high) creates more asphalted streets in the form of East-West canyons (2.8-3.5m) than North-South canyons (8-10m). There are predominantly two types in the settlement - a ground + 3 typology (80% of blocks) where the ground and first floors were severely affected by the floods while the rest are of ground typology, which were washed away. The work is divided into two sections - Outdoor microclimate studies analyse street typologies and indoor studies compare thermal performance of units.

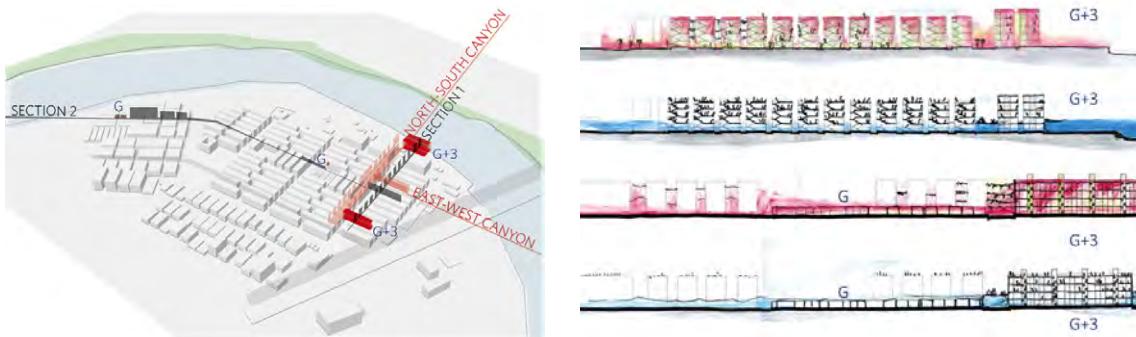


Figure 7. Sections and types (G+3/G) – orientation, behaviour during summer and monsoons

## Analytical work – existing fabric

### *Outdoor microclimate – street typologies*

The canyon geometry was analysed for solar access, wind velocity (sea breeze from the East) and existing outdoor conditions with Envimet (32°C average DBT, concrete construction and asphalt ground during Summer (May) and the following observations were made (fig 8) – The East-West canyon (30% Sky View Factor and Height-Width ratio 5:1) restricts more solar radiation than the North-South canyon (52% sky view factor and Height-width ratio 3.7:1) as a result of street geometry, morphology and sky view factor. At 14:00 hrs, the North-South canyon achieves a Dry Bulb temperature of 42°C while the East-West canyon achieved 39°C. At 2:00 hrs, the North-South canyon and East-West canyon both achieve 29°C. This indicates the North-South canyon re-radiated faster (higher sky view factor) than the East-West which behaved as a heat sink (Oke 1981). However, the wind velocity in the canyons was lower because of the lack of stacks, systematic open spaces and staggered edges which does not allow heat trapped in the lower layers to be dissipated to the upper layers. Also, the 180° orientation of blocks allows wind but 90° orientation blocks the flow. In addition, the river to the North modulates temperatures considerably.

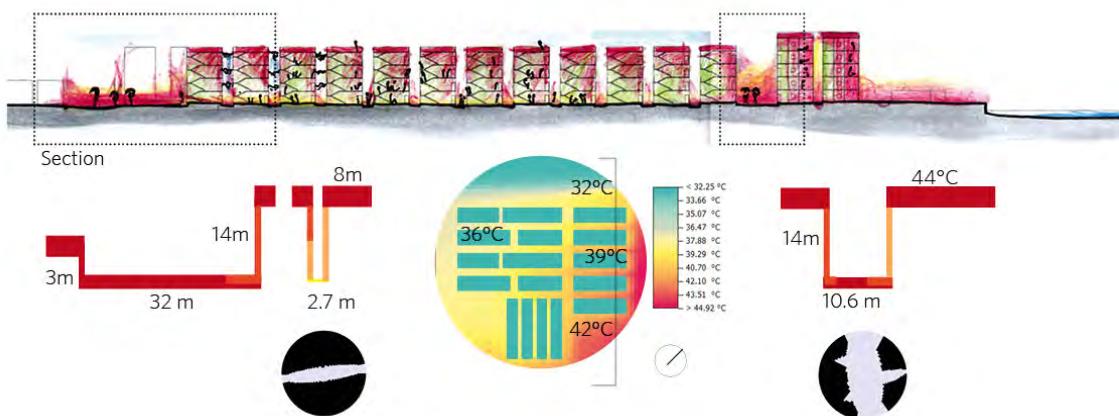


Figure 8. Typical canyon types - East-West (2.7m), North-South (10.6m) and Envimet analysis

### *Indoor – unit typologies*

The Ground+3 type typical flat (fig 9) consists of a living room, kitchen, bed and bath organised within 9.5x3.4x3m (4-6 people) of permanent concrete frame construction. The

Ground type is 6x4x3-3.5m high consisting of two multipurpose rooms with a bath (5 people) of temporary local wood and metal sheet construction.

A comparative study using dynamic thermal simulation (TAS 9.xx software) showed that indoor units (62%) have double the tendency to be out of comfort when comparing the Dry Bulb Temperatures. The G+3 type performed better (figure 11) than the G type because of obstruction from the context and materiality. However, hot air from the kitchen moved into the living room, instead of being expelled due to the lack of cross ventilation or stacks. In addition lack of night time ventilation increased hot conditions during the night. In case of semi-open areas, the stairwell had a maximum of 47% out of comfort hours, the in-between zones recorded 42% and the DBT recorded 31% indicating that urban morphology, materiality and anthropogenic heat sources caused heat retention. Therefore, strategies have been proposed to achieve indoor comfort (fig 11):

- a) Ventilation- Night time cross and stack ventilation and the use of the stairwell to expel heat from indoor and semi-open spaces during the night to cooler outdoors.
- b) Solar radiation- Shading surfaces (facades, windows, ground and roofs) exposed to solar radiation. Vegetative walls induced evaporative cooling bringing down temperatures by 3°C (Saito et al, 1990). Roof layers act as insulation and offer scoop ventilation.
- c) Daylight - The design sky illuminance of 22,000 lux requires small openings for light, reducing the perception of heat.

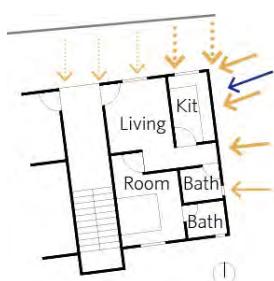


Figure 9. Typical plan

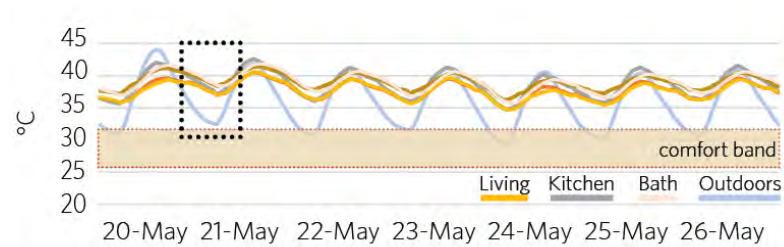


Figure 10. TAS Analysis (May 20-26) showing lack of night time ventilation

### Site strategies

The proposal involves a fluid strategy which revolves around the recycling economy using the river as its main mode of movement. It aims to turn the site from inward-looking to oriented towards the river (fig 11). This includes bringing the river into the site in the form of channels which will reduce temperatures in the interior and help in percolation. The different areas of the site are for the arrival areas for raw materials, distribution areas and workspaces. Two areas are detailed design interventions – existing street based and new floating typologies.

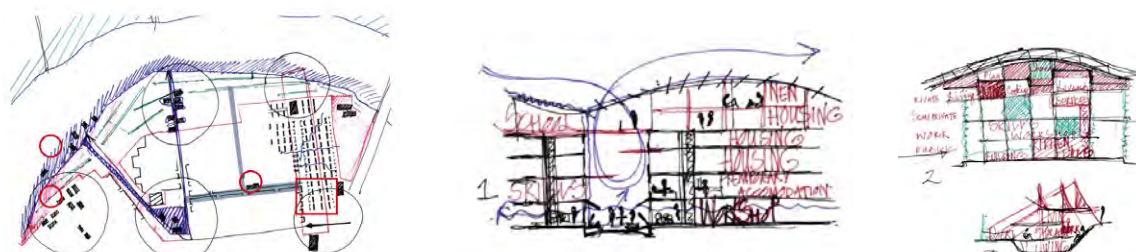


Figure 11. Site strategies – Street-based and floating types

## Propositions – existing streetscape

### Street based typologies

The intervention for the existing typologies included four stages – introduction of a new horizontal (0-6m high - fig 12.2) to mitigate floods and become informal workspaces, reorganization of existing floors (6-12m) to improve organisation and ventilation, introduction of new floors (12-18m) to increase densities and a community roof (18-21m).

The results of tested outdoor concepts were that solar access (Ladybug software – fig 12.1 and 12.2) was reduced by 50% on the East and 80% on the streets. Wind study (Autodesk CFD – fig 12.3) simulations showed that wind velocity increases from 0 to 3m/s when the block is raised by 6m and a jagged roof creates turbulence. Outdoor microclimate modelling and simulation (Envimet - fig 12 A and B) showed that when concrete construction is replaced by brick, a permeable roof, earth on the ground, vegetation and water channels are introduced, the temperatures reduce from 42 to 31°C (North-South canyon) and 39 to 30°C (East-West canyon) at 14:00 hrs on May 15 (Summer – average temperature 35.2°C). At 02:00 hrs, both measured 29°C (same as the weather station). This shows that change of material decreased sensible heat in the canyons reducing temperatures by 5-6°C, water modified edge temperatures extensively by 7-10°C, earth (instead of the asphalt) reduced temperatures by about 6°C and vegetation reduced temperatures by 2-3°C. For indoor existing units, the kitchen was reorganised and new stack windows of 24-28% window to floor area for 6m<sup>2</sup> and 45-55% for 9m<sup>2</sup> on North-South facades, and 30% for 3.5 m<sup>2</sup> on East-West facades (with shading) required. The new floors included staggered unit floor profiles to create turbulence for wind and outdoor living rooms for residents. Here, the living rooms and kitchen are combined into one cross ventilated space, built with mud, tile and stone aggregates.

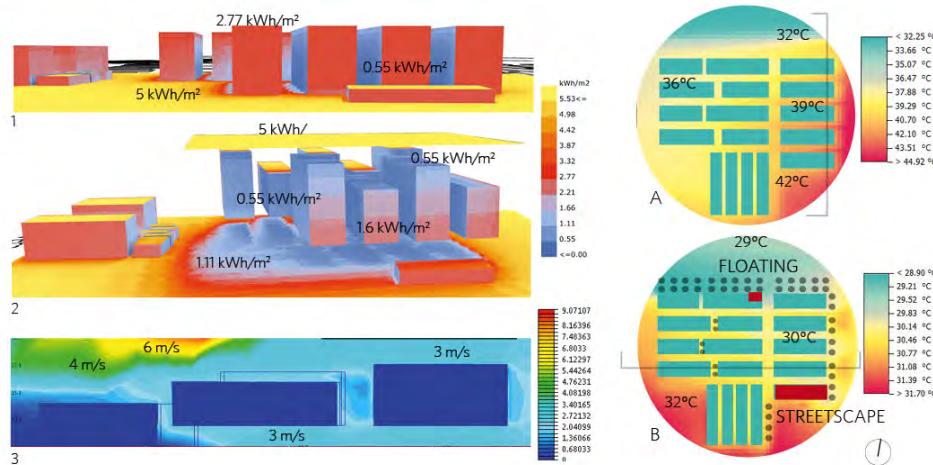


Figure 12. Monthly average daily solar radiation (1 - existing, 2 - proposed), wind studies (3 - proposed) and Envimet Comparative Analysis (A and B)

### Floating typologies

Floating typologies (fig 13) use the principles from the street typologies to house residents of the Ground typologies (largest risk to floods). The ground has workspaces, while living units (3x3x5.5m) and communal kitchens areas are lifted off the ground by 3m. Solar access was reduced by the larger insulated roof and inverted profiles beneath. The ventilation

strategies included monsoon windows, small openings at floor and large stacks near roof to increase extraction of heat. Vegetative walls on East and West induced evaporative cooling. To mitigate flooding, the type is a light weight structure of metal, wood and coconut pith boards placed on a framework of PET bottles and binding wire.



Figure 13. Configuration

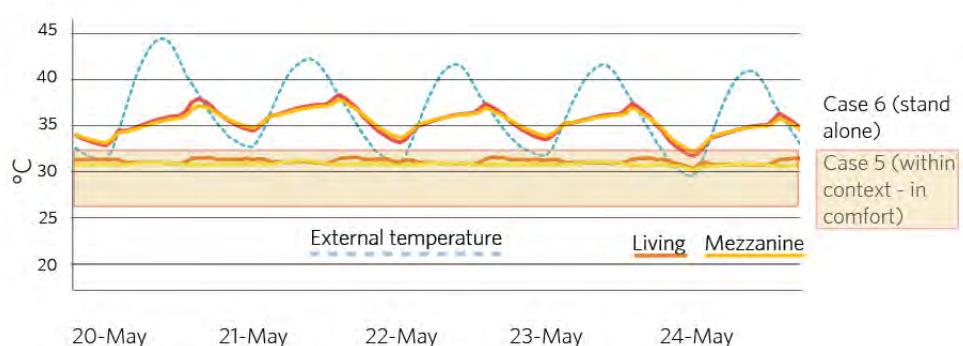


Figure 14. Case 5 + 6 TAS Comparative Analysis

### TAS Analysis – floating typologies

Cases 1-5 were tested as stand-alone units without surrounding context during May 20-24 (Summer) to examine whether they perform within the comfort range of 26-32°C. Case 1 tested a shoebox of wooden walls within a metal framework and coconut fibre boards as insulation. The units were out of comfort in comparison with diurnal DBT of 32-42°C. Case 2 included windows (2x1.2m on North-South) and stacks (1.5x.5m at 2.1 and 5m) which were enabled between 19-32°C and 90% open. Here, temperatures are in tandem with the DBT indicating the need for shading and ventilation regimes for different window sizes. Case 3 included louvered shading, stacks in floor and extensive night time ventilation instead of day time to achieve resultant temperatures of 32 to 36°C. Case 4 included internal gains of 2 people in each (9m<sup>2</sup>) unit of the living, kitchen and bath zones with different schedules. Here, the units come into range during the night.

Case 5 and 6 (fig 14) tested the principles from the outdoor analysis in Envimet. Case 5 included context (urban layout) and vegetative walls, the river and permeable ground and case 6 was tested without. Case 5 was in comfort but Case 6 required extra shading for exposed surfaces - vegetation for walls, bamboo mat shading for the roof and thicker light weight insulation.

### Conclusions

The design interventions focused on a riverside tenement block in a metropolis susceptible to urban heat islands and floods, in part aggravated by El-Nino-mediated climatic disturbances, but also caused due to anthropogenic interventions. Therefore, in addition to redevelopment of the riverside tenement block, the urban strategies also aimed at integrating the tenements by using the river and the recycling economy as a source of production. The materials derived from debris and garbage around the area is reused and re-integrated into different interfaces of the built areas to provide affordable respite to the UHI effect and mitigate the effects of flooding during the monsoons.

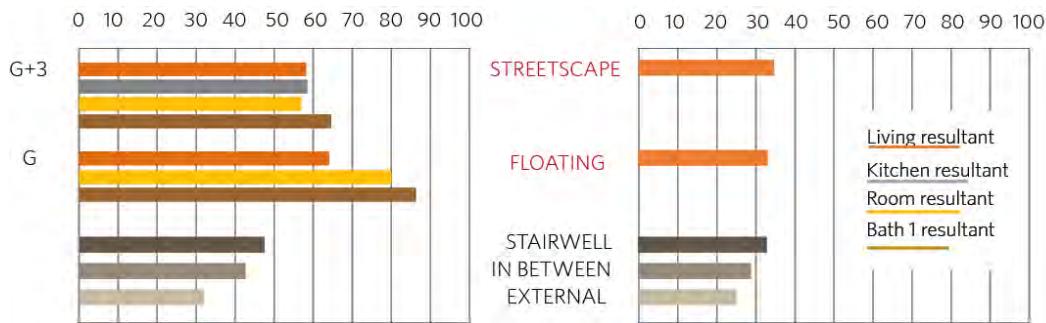


Figure 15. % of out of comfort hours : Comparison between existing (left), retrofitted and new types (right)

The streetscape type – redevelopment from existing G+3 typology into a G+5 type employs heavy weight material while the floating type (replacement for the ground type) is built from lightweight materials resting on a floating mechanism. By employing outdoor and indoor strategies, these permeable materials are tested reducing discomfort hours in the indoors by almost 50% and in the in-between areas by 12-15% (fig 15) throughout the year. This is achieved by transitional areas, shaded streets, screens and staggered buffer zones without compromising on density in order to house low income residents. The proposal aims to involve residents in a participatory process of regulating their microclimate, generating income and claiming ownership of unfavoured areas along rivers in fast developing metropolises.

## Acknowledgments

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## References

- Amirtham et al, (2009). Mapping of Micro-Urban Heat Islands and Land. *The International Journal of Climate Change: Impacts*, 1(2), pp 72-83.
- Amirtham, L. R., (2016). Urbanization and its impact on Urban Heat Island Intensity in Chennai Metropolitan Area, India. *Indian Journal of Science and Technology*, Volume 9(5).
- Jeganathan et al, (2012). Temperature trends of Chennai City, India. *Theoretical and Applied Climatology* 111(3-4),
- Landsberg, H., (1981). *The Urban Climate*. New York: Academic Press.
- Nleworks.com. (2017). Makoko Floating School | NLÉ. [online] Available at: <http://www.nleworks.com/case/makoko-floating-school/> [Accessed 16 Feb. 2016].
- Oke, T. R., (1987). *Boundary layer climates*. London: Routledge.
- Ramachandran et al, (2016). Visualization of Urban Growth Pattern in Chennai Using Geoinformatics and Spatial Metrics. *Journal of the Indian Society of Remote Sensing*, 44(4), pp 617-633.
- Saito I, I. O. K. T., 1990. Study of the effect of green areas on the thermal environment in an urban area. *Energy and Buildings*, s.l.: s.n.
- Santamouris, M., 2002. *Energy and Climate in the Urban built Environment*. London: James and James



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Method for definition of climatic classification based on human comfort

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**Abstract:** There are some climatic classifications that are already globally recognized. In a large scale, the most used classification is the one developed by Köppen (1936). For Mexico, García (1973) adapted those postulates to the climatic characteristics of the country and produced a specific classification of the climates. Both classifications were based on different variables such as mean annual and monthly rainfall, and mean annual and monthly temperature, but the main variable was the vegetation. This kind of classification was made for the use of natural resources but not for the human environment design. In this study, the climatic classifications are based on thermal and higric comfort for humans. The proposal method was tried for eight cities of four different climates of Mexico. An effect was found named "the blanket effect" that modifies the status of every city to be in the cold. A correction step was rehearsed with good agreement with reality. Nine basic status for weather conditions were settled: comfort, hot, cold, humid, dry, hot dry, hot humid, cold humid and cold dry. Also, a correlation coefficient of  $r=-0.925$  was found between thermal swing and mean RH for 96 cities over all the country. As conclusion, the classification founded show good agreement with common knowledge of the climate, nevertheless it is necessary to extend this study to validate the method.

**Keywords:** climatic classification, blanket effect, bioclimatic chart, human comfort, human environment.

### Introduction

Weather/climate, from Greek *Klīmat*, is usually defined as the state or condition of a region averaged over a series of years, with respect of the atmospheric variables such as wind, air temperature, moisture, pressure, cloudiness, precipitation and sunshine. In architecture, these variables are the source of the inner conditions of our designs. For this, it becomes more than fundamental to knowing the climate of project settle down in order to design it with climate and not against it.

Most of the actual climate classification are based in variables that not necessarily are related to the human comfort such as vegetation, rainfall, cloudiness, distance from the sea, latitude or altitude. Dry bulb temperature and RH are two of the most important variables to define human comfort. These two variables are not the main inputs in most of the climate charts. In this study, a method for index the climate from thermal human comfort standard is presented. Also, a new concept is introduced, the blanket effect. It helps to modify the values of the control task from lower temperatures to have better agreement with common perception of the people.

## Background

In 1936, Vladimir Köppen (Köppen & Geiger 1936) published three of five books series named “handbuch der Klimatologie”. After years, Geiger finished Köppen’s work completing the other two books. In these books, Köppen section the world in five great climatic groups (Köppen & Geiger 1936, p.13):

A	Tropische Regenklimate	Tropical
B	Trockenklimate	Dry
C	Warmgemäßigte	Warm
D	Boreale Klimate	Boreal
E	Schneeklimate	Snowy or perpetual ice (Polar)

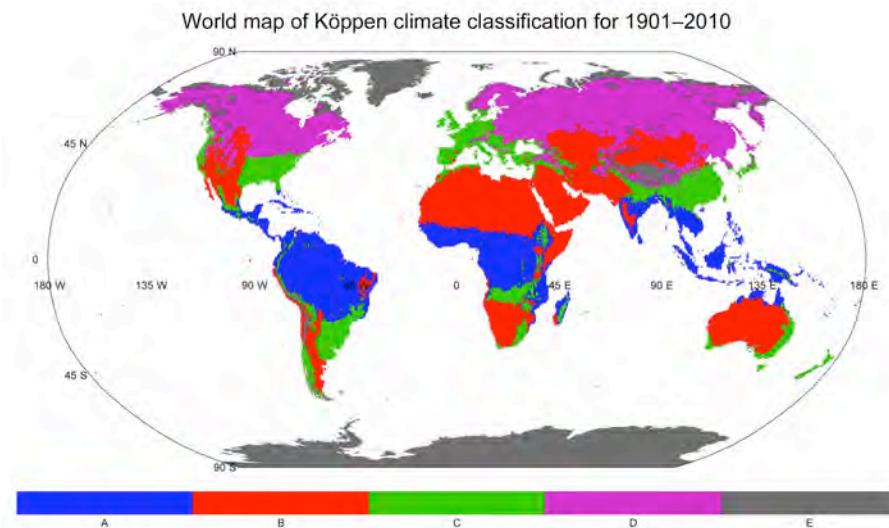


Figure 1. World map of Köppen climate classification. Source: Chen & Chen (2013, p.72)

These general groups are divided in smaller subgroups defined by the humidity, especially for rainfall:

For group A

m monsoon                          Humid with short dry season and abundant rainfall

For group A, C and D

f Equatorial                          Humid without dry season and rainfall all year

s    Dry season in summer and rainfall in winter

w savanna                            Dry season in winter and rainfall in summer

For group B

S steppe                             semi-arid

W deserted                           arid

For group E

T tundra                            dry, average temperature of hottest month between 0° and 10°C

F perpetual ice                    dry, average temperature of hottest month under 0°C

There are other descriptors that have been added due the incomplete work of the botanic Köppen. It is important to point that this kind of classifications was designed for agronomical purposes, then, its principal variables are not for human purposes. I.e., the first variable to delimitated climate is the vegetation. Köppen says that vegetation has a strong relationship with the climate conditions of a region. Subsequently, He determined a climate group studying and joining vegetal species and its requirements.

Second descriptor, rainfall or humidity, also comes from vegetation's requirements. It indicates the amount of water that can be found in a territory and the time in the year when it falls in order to designate the time of sowing or harvest. There is a third descriptor what assess the temperature. It is in the second and third descriptors when it is possible to find variables that are relative to the human comfort conditions, i.e., dry bulb temperature and RH.

Koenisberger (1977) and Evans (1980; 2007) defined in different documents climate types or zones with their meteorological variables features and presented their design recommendations for each type. Evans (2007, pp.27–30) presented three types of tropical climates: warm-humid, hot-dry and monsoon or transitional, and added three sub-climates: upland, maritime desert and tropical island.

He defined each climate zone using different variables like geographical: latitude, altitude and distance from water-land masses, and climate variables: average temperatures, thermal swing, relative humidity, cloudiness, rainfall, wind and sunshine (See table 1)

Table 1. Climate zones summary for tropical regions. Source: Evans (2007, p.30)

Climatic variable		Warm humid	Hot dry	Comfort	Cold	Very cold
Typical temperature °C		20 – 30	15 – 35	15 – 25	5 - 15	< 5
Relative humidity %		> 80 %	< 60 %	60 – 80	-	-
Temperature swing deg C		< 10° C	> 12° C	8 – 12	< 10° C	-
Climate classification	Latitude					
Warm humid	0 -15°	X				
Hot dry	20 - 35°		X	X		
Transition	10 - 30°	X	X	X		
Monsoon	5 - 30°	X	X	(X)	X	
Equatorial upland	0 - 20°			X	(X)	
Maritime desert	20 - 35	X	X			
Subtropical	30 - 40	(X)	X	X	X	
Temperate	40 - 50			X	X	
Alpine-Andean	30 - 50			X	X	X
Cool temperate	40 - 55			X	X	
Cold	> 50°			(X)	X	X
Very cold	> 60°				X	X

It is important to mention that Evans made a review and an analysis of the relation between the RH and the thermal swing. He emphasis the indirect relation of this two variables in chapter 7 of his thesis: "*with low humidity related to higher (thermal) swings...*" (Evans 2007, p.290).

Other climatic classifications were formulated from different variables along the last century, for instance, in brazil, Roriz (2012) made a proposal climatic classification using temperatures, thermal swing and RH for humidity and others variables as latitude, altitude, distance from the sea. In Mexico, García (1973) made a modification of the climatic system of Köppen to adjust the Köppen's chart to the country. Obviously, her principal variable was the vegetation. Morillón (2002; 2003) presented different bioclimatic charts for each month but the method is not clear established. Fuentes (2009; Rodríguez Viqueira et al. 2011; 2014) did a climatic classification from the bioclimatic requirements but the humidity subject was tried from the rainfall instead the RH. Finally, Gómez (2009) tried a classification for a region of Jalisco, Mexico. In his study, he found that most of the cities analysed using the adaptive comfort and degree-days for the control task indicates that are in cold. He proposed a correction value, but the justification was not clear enough. In this study, the correction step named "blanket effect" is presented.

## Method

Eight cities with different climatic conditions of Mexico were analyzed. Two for each popular knowing characteristic climatic condition: dry extreme (Mexicali and Nogales), cold (Toluca and Pachuca), hot humid (Merida and Tuxtla Gutierrez) and warm (Morelia and Cuernavaca). The climatic data used was obtained from the meteorological national service normals. These information presents the climatic conditions for each climatic station in a thirty years period. For this study, the normals used was from 1981-2010 period.

The data presented in those normals are the maximum, average and minimum temperatures, so the RH was calculated using the method developed by Tejeda (Tejeda Martínez 2007). Also, the hourly temperatures and RH for each month was calculated using the same process (See table 2)

Table 2. Example of hourly temperatures and RH of each month for Mexicali, Baja California Norte, Mexico.

City: Mexicali		Lat: 32.66 °N		Long: 115.5 °W		Altitude: 3 masl												
Hour		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual				
00:00		10.3	10.8	15.7	17.8	21.9	25.4	29.4	29.7	25.4	21.2	13.8	9.3	19.2				
01:00		9.0	9.6	14.3	16.6	20.7	24.3	28.4	28.7	24.1	19.8	12.6	8.1	18.0				
02:00		8.0	8.6	13.1	15.6	19.7	23.3	27.6	27.8	23.0	18.6	11.6	7.2	17.0				
03:00		7.2	7.7	12.1	14.8	18.9	22.5	26.9	27.1	22.1	17.7	10.7	6.3	16.2				
04:00		6.5	7.1	11.3	14.1	18.2	21.9	26.4	26.6	21.4	16.8	10.1	5.7	15.5				
05:00		6.0	6.5	10.6	13.5	17.6	19.4	25.9	26.1	20.7	16.2	9.6	5.2	14.8				
06:00		5.6	6.1	10.1	11.4	15.9	19.9	24.5	24.4	18.4	15.6	9.1	4.7	13.8				
07:00		4.2	4.8	8.3	12.4	17.8	22.4	26.5	25.6	18.9	13.7	7.8	4.4	13.9				
08:00		4.5	5.7	10.4	15.3	21.7	26.6	29.9	28.4	21.3	15.0	8.3	3.6	15.9				
09:00		6.5	8.5	14.3	19.6	26.5	31.5	34.2	32.3	25.4	18.2	10.4	5.3	19.4				
10:00		10.1	12.9	19.3	24.2	31.3	36.2	38.2	36.3	30.1	22.6	14.2	8.6	23.7				
11:00		14.5	17.6	24.1	28.3	35.2	39.9	41.4	39.8	34.6	27.2	18.6	12.8	27.8				
12:00		18.6	21.7	28.1	31.4	37.9	42.3	43.6	42.2	38.1	31.2	22.8	16.8	31.2				
13:00		21.8	24.7	30.8	33.2	39.3	43.4	44.7	43.6	40.4	34.0	25.9	20.0	33.5				
14:00		23.8	26.3	32.1	33.9	39.5	43.4	44.7	44.0	41.4	35.6	27.7	22.0	34.5				
15:00		24.5	26.6	32.3	33.5	38.7	42.4	43.9	43.5	41.3	36.1	28.3	22.8	34.5				
16:00		24.1	25.8	31.5	32.4	37.2	40.8	42.6	42.4	40.3	35.5	27.8	22.5	33.6				
17:00		23.0	24.3	29.9	30.7	35.3	38.8	40.9	40.9	38.8	34.3	26.6	21.5	32.1				
18:00		21.3	22.4	27.9	28.8	33.1	36.6	39.0	39.1	36.8	32.6	24.8	19.9	30.2				
19:00		19.3	20.2	25.7	26.7	30.9	34.3	37.1	37.3	34.7	30.6	22.8	18.0	28.1				
20:00		17.2	18.0	23.5	24.6	28.7	32.2	35.3	35.5	32.6	28.5	20.7	16.1	26.1				
21:00		15.2	15.9	21.3	22.6	26.7	30.2	33.5	33.8	30.5	26.4	18.7	14.1	24.1				
22:00		13.4	13.9	19.2	20.8	24.9	28.4	32.0	32.3	28.6	24.5	16.9	12.3	22.3				
23:00		11.7	12.3	17.4	19.2	23.3	26.8	30.6	30.9	26.9	22.7	15.2	10.7	20.7				
Max		24.5	26.6	32.3	33.9	39.5	43.4	44.7	44.0	41.4	36.1	28.3	22.8	44.7				
Min		4.2	4.8	8.3	11.4	15.9	19.4	24.5	24.4	18.4	13.7	7.8	3.6	3.6				
Swing		20.3	21.8	24.0	22.4	23.6	24.0	20.1	19.6	23.0	22.4	20.5	19.1	21.7				
Average		13.6	14.9	20.1	22.6	27.5	31.4	34.5	34.1	29.8	24.8	17.3	12.4	23.6				

A correlation between RH and thermal swing was found using data from the 96 biggest cities of the country in order to used thermal swing instead RH to determine the humidity of the region (See Fig. 2). The correlation coefficient of  $r=0.925$  of a negative correlation was found and a  $r^2=0.857$  ( $n=1152$ ,  $se=1.18$ ).

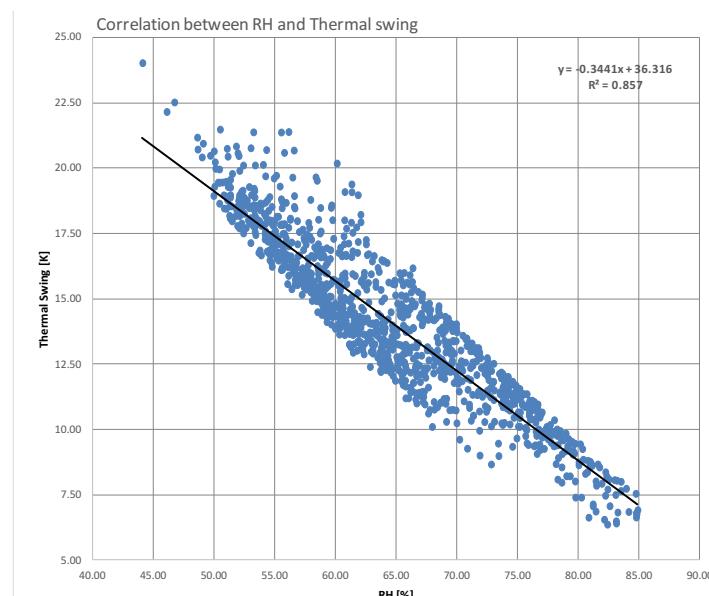


Figure 2. Correlation between RH and Thermal swing for 96 cities of Mexico.

With the equation founded, the proposal condition for dryness, higric comfort and humidity was established (See table 3).

Table 3. RH and thermal swing for each climatic condition.

RH	Thermal Swing	Condition
Less than 30%	Up to 25.9 K	Dry
Between 30% and 70%	Between 25.9-12.2 K	Comfort
Higher than 70%	Less than 12.2 K	Humid

The comfort temperature was calculated using the ANSI-ASHRAE standard (ASHRAE STANDARD 2010) for the adaptive thermal comfort for each month of every location. The amplitude was established in 2.5 K according with Auliciems and Szokolay (1997, p.59).

Then, with the hourly temperatures and RH and the comfort zone, degree-days (McGilligan et al. 2011)(Mourshed 2012) was calculated and summarised to identify the daily comfort task for each month to heat, cool, humidify and de-humidify (See Table 4).

It was noticed that in the 8 cities analysed, the annual results did not agree with the common perception of the people, and much less with the current and accepted climatic classifications. In the degree-days tables was noticed that most of the time, the temperature remains in cold below the comfort zone but in that hours, people did not notice those temperatures.

A **Blanket effect** was defined as those hours were human being is asleep and unconscious of the thermal environment in the space where he sleeps. Normally, the studies of thermal comfort made their questionnaires during daytime where people is conscious of their environmental conditions, therefore, they can express or notice comfort or discomfort. It could be said that during night time, the threshold to express discomfort is bigger than daytime, i.e., human being requires to be in higher cold or hot to wake up from sleep mode and modify the conditions of his space.

Also, there are many passive strategies to achieve comfort during night time such as increasing clo by pyjamas, bed sheet, blankets and so on, turn on/off fan or air conditioning, open/close windows.

Table 4. Deficit and surplus daily temperatures [K] for each month, Mexicali, Baja California Norte, Mexico.

City: Mexicali	Lat:	32.66 °N	Long:	115.5 °W	Altitude:	3 masl	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
Hour																				
00:00	-9.5	-9.4	-5.8	-4.5	-2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.9	-7.1	-10.0	-50.2		
01:00	-10.7	-10.6	-7.3	-5.7	-3.2	-0.8	0.0	0.0	0.0	0.0	-0.5	-1.6	-3.2	-8.3	-11.2	-11.2	-61.5			
02:00	-11.7	-11.6	-8.5	-6.7	-4.2	-1.8	0.0	0.0	0.0	0.0	-1.6	-4.4	-9.3	-12.2	-12.2	-71.9				
03:00	-12.5	-12.4	-9.5	-7.6	-5.0	-2.6	0.0	0.0	0.0	0.0	-2.5	-5.4	-10.1	-13.0	-13.0	-80.6				
04:00	-13.2	-13.1	-10.3	-8.3	-5.7	-3.2	0.0	0.0	0.0	0.0	-3.3	-6.2	-10.8	-13.7	-13.7	-87.7				
05:00	-13.7	-13.6	-11.0	-8.8	-6.2	-5.7	-0.1	0.0	0.0	0.0	-3.9	-6.9	-11.3	-14.2	-14.2	-95.5				
06:00	-14.2	-14.0	-11.5	-10.9	-8.0	-5.2	-1.5	-1.5	-1.5	-6.2	-7.4	-11.7	-14.6	-14.6	-106.8					
07:00	-15.5	-15.3	-13.3	-9.9	-6.1	-2.7	0.0	0.0	0.0	0.0	-5.7	-9.3	-13.1	-14.9	-14.9	-106.2				
08:00	-15.2	-14.4	-11.2	-7.0	-2.2	0.0	0.0	0.0	0.0	0.0	-3.3	-8.0	-12.6	-15.7	-15.7	-89.7				
09:00	-13.3	-11.6	-7.3	-2.8	0.0	1.4	3.1	1.4	1.4	0.0	0.0	-4.8	-10.5	-14.1	-14.1	-58.2				
10:00	-9.7	-7.3	-2.3	0.0	2.4	6.1	7.2	5.4	0.5	-0.4	-6.7	-10.7	-15.5							
11:00	-5.3	-2.5	0.0	1.0	6.3	9.8	10.4	8.8	5.0	0.0	-2.2	-6.6	-24.7							
12:00	-1.1	0.0	1.5	4.0	9.0	12.2	12.6	11.3	8.5	3.1	0.0	-2.6	-58.6							
13:00	0.0	0.0	4.2	5.9	10.4	13.3	13.6	12.7	10.7	6.0	0.0	0.0	76.8							
14:00	0.0	1.1	5.5	6.5	10.6	13.3	13.7	13.1	11.8	7.6	1.8	0.0	85.0							
15:00	0.0	1.4	5.7	6.1	9.8	12.3	12.9	12.6	11.7	8.0	2.4	0.0	83.0							
16:00	0.0	0.7	4.9	5.0	8.3	10.7	11.6	11.5	10.7	7.5	2.0	0.0	72.8							
17:00	0.0	0.0	3.3	3.4	6.4	8.7	9.9	10.0	9.2	6.3	0.7	0.0	57.8							
18:00	0.0	0.0	1.4	1.4	4.3	6.5	8.0	8.2	7.2	4.5	0.0	0.0	41.5							
19:00	-0.4	0.0	0.0	0.0	2.0	4.2	6.1	6.4	5.1	2.5	0.0	-1.3	24.7							
20:00	-2.5	-2.2	0.0	0.0	0.0	2.1	4.2	4.6	3.0	0.5	-0.1	-3.3	6.2							
21:00	-4.5	-4.3	-0.3	0.0	0.0	0.1	2.5	2.9	0.9	0.0	-2.2	-5.2	-10.0							
22:00	-6.4	-6.2	-2.4	-1.5	0.0	0.0	1.0	1.4	0.0	0.0	-4.0	-7.0	-25.1							
23:00	-8.0	-7.9	-4.2	-3.1	-0.6	0.0	0.0	0.0	0.0	-0.3	-5.7	-8.6	-38.4							
Average	-7.0	-6.4	-3.3	-1.8	1.1	3.3	4.8	4.5	2.4	-0.5	-4.9	-7.5	-15.3							
Total	-167.3	-153.2	-78.4	-43.6	26.3	78.9	115.1	108.4	57.4	-12.1	-118.8	-178.9	-366.3							
Deficit [°C]	-167.3	-156.5	-104.8	-76.9	-43.3	-22.0	-1.6	-1.9	-26.8	-58.2	-125.7	-178.9	-963.8							
Deficit [h]	18.0	16.0	14.0	12.0	10.0	7.0	2.0	2.0	8.0	12.0	16.0	18.0	135.0							
Surplus [°C]	0.0	3.2	26.4	33.3	69.6	100.8	116.7	110.3	84.2	46.0	6.9	0.0	597.5							
Surplus [h]	0.0	3.0	7.0	8.0	10.0	13.0	14.0	14.0	12.0	9.0	4.0	0.0	94.0							

To determine the hours where most of the people sleeps in every city, the consumptions of energy data were used from the national service (Comisión Federal de

Electricidad 2017) to identify in what hours the demand of energy increase or decrease. It was found that between 22:00 and 6:00 hours approximately, the consumption of energy decrease in the different regions of the country. Therefore, those hours were discarded from the degree-days average (the Blanket Effect Correction BEC) (See table 5).

Table 5. Deficit and surplus daily temperatures [K] for each month with blanket effect correction, Mexicali, Baja California, Mexico.

City: Mexicali	Lat:	32.66 °N	Long:	115.5 °W	Altitude:	3 masl							
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
00:00	-9.2	-9.1	-5.8	-4.5	-2.0	0.0	0.0	0.0	0.0	-1.8	-6.9	-9.8	-49.1
01:00	-10.5	-10.4	-7.2	-5.7	-3.1	-0.7	0.0	0.0	-0.4	-3.2	-8.1	-11.0	-60.3
02:00	-11.5	-11.4	-8.4	-6.7	-4.1	-1.7	0.0	0.0	-1.5	-4.3	-9.1	-12.0	-70.7
03:00	-12.3	-12.2	-9.4	-7.5	-5.0	-2.5	0.0	0.0	-2.4	-5.3	-9.9	-12.8	-79.4
04:00	-13.0	-12.9	-10.3	-8.2	-5.6	-3.2	0.0	0.0	-3.2	-6.1	-10.6	-13.5	-86.5
05:00	-13.5	-13.4	-10.9	-8.8	-6.2	-5.6	-0.1	0.0	-3.8	-6.8	-11.1	-14.0	-94.2
06:00	-13.9	-13.8	-11.5	-10.9	-8.0	-5.1	-1.4	-1.5	-6.1	-7.3	-11.5	-14.4	-105.5
07:00	-15.3	-15.1	-13.2	-9.9	-6.0	-2.7	0.0	-0.3	-5.6	-9.3	-12.9	-14.7	-105.0
08:00	-15.0	-14.2	-11.2	-7.0	-2.2	0.0	0.0	0.0	-3.2	-8.0	-12.4	-15.5	-88.6
09:00	-13.0	-11.4	-7.2	-2.7	0.0	1.5	3.2	1.4	0.0	-4.7	-10.2	-13.9	-57.1
10:00	-9.4	-7.0	-2.3	0.0	2.4	6.2	7.2	5.4	0.6	-3.0	-6.5	-10.6	-14.3
11:00	-5.1	-2.3	0.0	1.0	6.4	9.9	10.5	8.9	5.0	0.0	-2.0	-6.4	25.9
12:00	-0.9	0.0	1.5	4.1	9.1	12.3	12.6	11.4	8.5	3.2	0.0	-2.4	59.4
13:00	0.0	0.0	4.2	5.9	10.5	13.4	13.7	12.7	10.8	6.0	0.2	0.0	77.5
14:00	0.0	1.4	5.6	6.6	10.7	13.4	13.7	13.1	11.8	7.6	2.1	0.0	85.9
15:00	0.0	1.7	5.7	6.2	9.9	12.4	12.9	12.6	11.7	8.1	2.6	0.0	83.9
16:00	0.0	0.9	4.9	5.1	8.4	10.8	11.6	11.5	10.8	7.6	2.2	0.0	73.7
17:00	0.0	0.0	3.4	3.4	6.5	8.8	9.9	10.0	9.2	6.3	0.9	0.0	58.4
18:00	0.0	0.0	1.4	1.5	4.3	6.5	8.0	8.3	7.3	4.6	0.0	0.0	41.9
19:00	-0.2	0.0	0.0	0.0	2.1	4.3	6.1	6.4	5.2	2.6	0.0	-1.1	25.4
20:00	-2.3	-2.0	0.0	0.0	0.0	2.1	4.3	4.6	3.0	0.5	0.0	-3.1	7.3
21:00	-4.3	-4.1	-0.3	0.0	0.0	0.2	2.6	3.0	1.0	0.0	-1.9	-5.0	-8.9
22:00	-6.1	-6.0	-2.3	-1.5	0.0	0.0	1.0	1.4	0.0	0.0	-3.8	-6.8	-24.1
23:00	-7.8	-7.7	-4.2	-3.1	-0.6	0.0	0.0	0.0	0.0	-0.2	-5.4	-8.4	-37.3
Average	-5.0	-4.2	-1.2	0.1	3.2	5.5	6.8	6.4	4.1	1.0	-3.1	-5.5	8.0
Total	-85.6	-71.9	-21.2	1.9	53.9	94.0	115.8	109.1	70.1	16.8	-53.2	-93.8	135.8
Deficit [°C]	-85.6	-75.8	-48.0	-31.8	-16.2	-7.8	-1.4	-1.8	-15.0	-29.7	-61.2	-93.8	-468.1
Deficit [h]	11.0	9.0	7.0	5.0	3.0	2.0	1.0	2.0	3.0	5.0	8.0	11.0	67.0
Surplus [°C]	0.0	3.9	26.7	33.7	70.1	101.7	117.2	110.9	85.0	46.5	8.0	0.0	604.0
Surplus [h]	0.0	3.0	7.0	8.0	10.0	13.0	14.0	14.0	12.0	9.0	5.0	0.0	95.0

## Results and discussion

Figure 3 shows the average degree-day of every month for each location analysed. The hours in comfort zone were discarded, so it shows only the hours of control task. Most of the months and location remains in cold and requires heat to get in the comfort zone. Mexicali is the hottest location of the 8 cities. It appears from May through September in hot with almost 5 K degree day. Cities that normally are known as a hot and humid barely appears in hot, and not all the year, like Merida or Tuxtla Gutierrez (green).

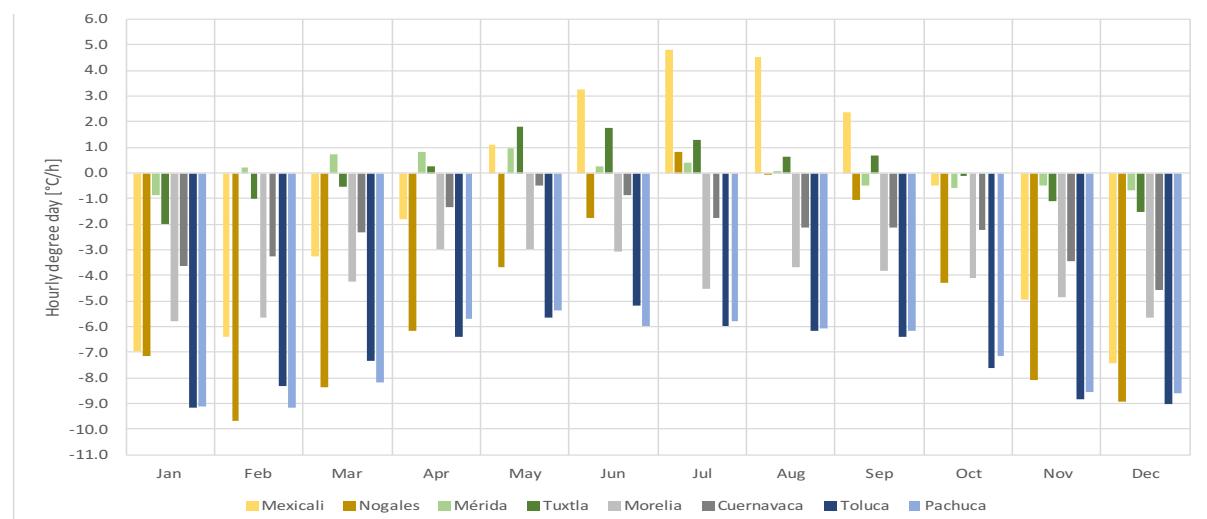


Figure 3. Average degree day of control task for each month and location.

After applying the BEC, the lag to be in cold was reduced in all the cities (See Fig. 4) Cities in green (known as hot humid) remains over the 0°C in the heat zone, this status agrees with the common perception of the people. Cities in blue (known as cold) remains below the 0°C

in the cold zone. Cities in yellow (dry extreme) remains in cold from January through April and from October through December (winter), and in hot from May through September (summer) according with the general perceptions of the people. Finally, cities in grey (warm) remains close to the 0°C of control task. They have their variations in less than 3°C/h.

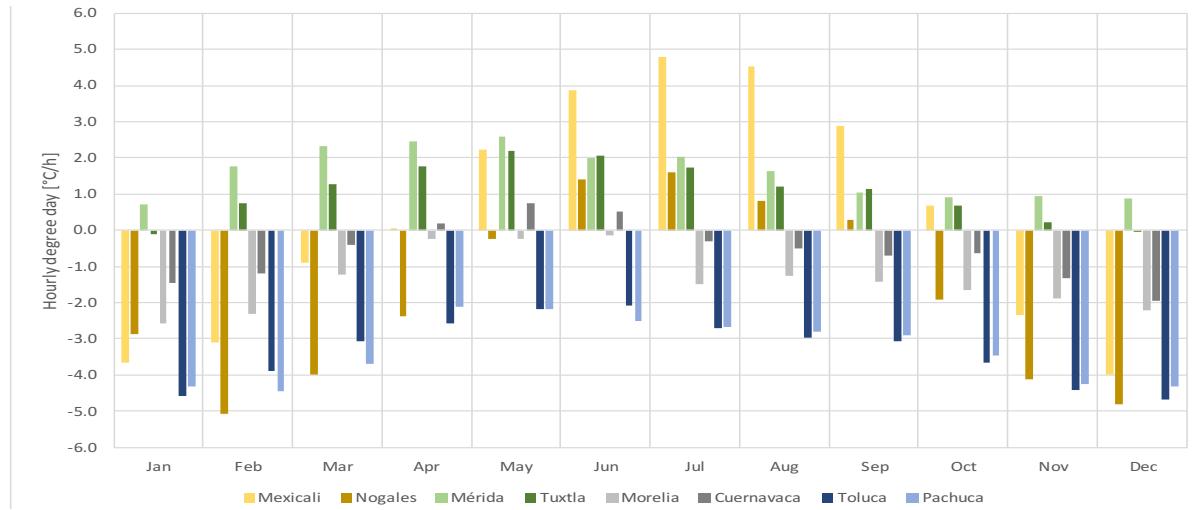


Figure 4. Average degree day of control task for each month and location after BEC.

In figure 5, control task and thermal swing are correlated to integrate the humidity to the classification. In the figure on the left, the values are presented without the correction of the blanket effect. Blue zone indicates cold, comfort thermal and higric in white, red is hot, brown is dryness and green is humidity. The corners are the combination of temperature and humidity.

In the left, most of the cities remains in cold but Mexicali, Mérida and Tuxtla Gutiérrez that appear in comfort. But if the blanket effect correction is applied, Cuernavaca gets inside the thermal comfort zone, Mérida and Tuxtla Gutiérrez almost get in the hot zone and Morelia and Nogales are in the limit between cold and comfort zones. The blue cities, continue in the cold zone, so the BEC does not affect considerably their performance as it does with the other cities that move them according to the real perception of their citizens.

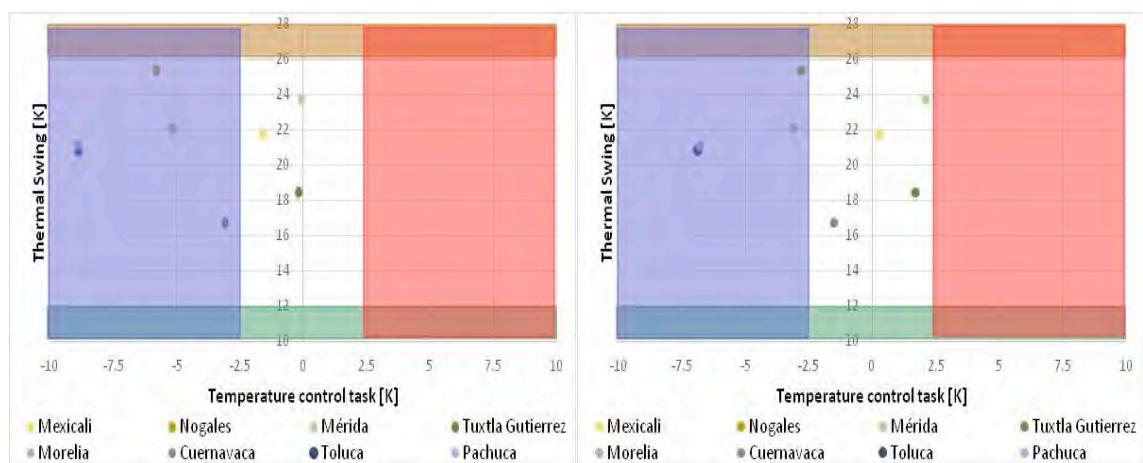


Figure 5. Control task and thermal swing correlation for the 8 cities analysed. Left without BEC, right with it.

## Conclusions

This study presented a method to sort the climate based in the human comfort guidelines. Eight cities of four different climates of Mexico were analysed. The blanket effect

correction was introduced to modified the values in cold to a better performance and agreement according with the perception of the people that lives in that cities. Also, a correlation of thermal swing and RH of the 96 biggest cities of Mexico was presented.

The values modified with the BEC show better relationship with the perception of the people and their climate than those without BEC. Nevertheless, the BEC seems to be not enough to correct the gap between reality and perception. It is possible that the BEC has some relationship with the circadian rhythm.

Further researches should aim to tune the limits of the blanket effect in terms of hours and restrictions and its possible relationship with the circadian rhythm. Also, should aims to adjust the correlation between the thermal swing and the RH to identify the confines of the climatic zones.

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## References

- ASHRAE STANDARD, 2010. *Thermal environmental conditions for Human Occupancy.*,  
Auliciems, A. & Szokolay, S. V, 1997. Thermal comfort. In *Passive and Low Energy Architecture International Design Tools and Techniques*. p. 68.
- Chen, D. & Chen, H.W., 2013. Using the Köppen classification to quantify climate variation and change: An example for 1901-2010. *Environmental Development*, 6(1), pp.69–79.
- Comisión Federal de Electricidad, 2017. Horas pico de consumo eléctrico. Available at: [http://app.cfe.gob.mx/Applicaciones/CCE/Tarifas/Tarifas/tarifas\\_negocio.asp?Tarifa=HM](http://app.cfe.gob.mx/Applicaciones/CCE/Tarifas/Tarifas/tarifas_negocio.asp?Tarifa=HM).
- Evans, J.M., 1980. *Housing, Climate and Comfort*, London, UK: Architectural Press.
- Evans, J.M., 2007. *The Comfort Triangles: A New Tool for Bioclimatic Design*.
- Freixanet, A.F., 2009. Modelo de análisis climático y definición de estrategias de diseño bioclimático para diferentes regiones de la república mexicana.
- Fuentes Freixanet, V.A., 2014. *Mapas bioclimáticos de la República Mexicana* 1ra edición., México D.F.: Universidad Autónoma Metropolitana.
- García, E., 1973. *Modificaciones al sistema de clasificación climática de Köppen* Segunda ed., México D.F.: Universidad Nacional Autónoma de México.
- Gómez-Amador, A., 2009. Atlas bioclimático de Jalisco. In J. Secretaría del medio ambiente para el desarrollo sustentable, ed. *Edificación sustentable en Jalisco*. Guadalajara, Jalisco, pp. 42–61.
- Koenigsberger, O.H. et al., 1977. *Viviendas y edificios en zonas cálidas y tropicales* 1er ed., Madrid: Paraninfo.
- Köppen, W. & Geiger, R., 1936. *Handbuch der Klimatologie*, Berlin.
- McGilligan, C., Natarajan, S. & Nikolopoulou, M., 2011. Adaptive comfort degree-days: A metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates. *Energy and Buildings*, 43(10), pp.2767–2778. Available at: <http://dx.doi.org/10.1016/j.enbuild.2011.06.037>.
- Morillón G., D. et al., 2002. Atlas Bioclimático De La República Mexicana. *Energías Renovables y Medio Ambiente*, 10, pp.57–62.
- Morillón Gálvez, D., 2003. Mapas de bioclima de la República Mexicana. In E. L. S. A. de C.V., ed. *Estudios de arquitectura bioclimática*. México D.F., pp. 117–130.
- Mourshed, M., 2012. Relationship between annual mean temperature and degree-days. *Energy and Buildings*, 54, pp.418–425. Available at: <http://dx.doi.org/10.1016/j.enbuild.2012.07.024>.
- Rodríguez Viqueira, M. et al., 2011. *Introducción a la Arquitectura Bioclimática* 1ra edición., México D.F.: Editorial Limusa S.A. de C.V.
- Roriz, M., 2012. *Uma proposta de revisao do zoneamento bioclimático Brasileiro*, Sao Paulo.
- Tejeda Martínez, A., 2007. On the evaluation of the wet bulb temperature as a function of dry bulb temperature and relative humidity. *Atmósfera*, 3.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The impact of shading levels on users' thermal comfort in public leisure spaces

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**Abstract:** The knowledge about microclimate and its influence on people's thermal comfort becomes critical to the planning process of all types of environment. In leisure facility design, guaranteeing the user's thermal comfort has become increasingly essential, since it affects the activities, usage characteristics and the time people spent in these spaces. Recent researches on thermal comfort aim at creating guidelines for attractive outdoor environments that contribute to improve urban quality of life and consider environmental factors (air temperature, wind speed and relative humidity), which affect the users' thermal perception and satisfaction. In this context, this pilot project of a larger project investigated how the different levels of shading affect users' thermal comfort in outdoor leisure spaces. It was conducted in Bauru Municipal Zoo Park, São Paulo State, Brazil, through the analysis of microclimatic research, questionnaires, and field observations in cold weather conditions for three days. These surveys allowed to identify the actual sensation votes (ASV) calculated through the PET index (Physiological Equivalent Temperature), in two subspaces with the same attractiveness and different levels of shading. The analysis of the results highlighted: 1.Great number of comfortable users' in the area with greater shading during times of greater solar heating; 2. Users' short exposure in the area of high incidence of direct solar radiation; and 3. Range of thermal neutrality in the PET index varied in relation to the two subspaces. The results show the close relationship between levels of shading, thermal comfort and exposure time in the outdoor space.

**Keywords:** Outdoor thermal comfort, time exposure, levels of shading, PET index, urban parks.

## **Introduction**

Urban parks composed of large green areas are key environments for people's well-being, as they have the purpose of improving the quality of life through leisure offer, landscaping and environmental preservation.

Studies in various climatic and cultural contexts have emphasized the thermal comfort in outdoor spaces, since they affect the activities and usage characteristics of users in squares and parks (NIKOLOPOULOU; BAKER; STEEMERS, 2001; ZACHARIAS; STATHOPOULOS; WU, 2001; THORSSON; LINDQVIST; LINDQVIST, 2004; THORSSON et al., 2007; LIN, 2009 and LABAKI et al., 2012). These researches seek to provide subsidies for the creation of attractive external environments, which favor daily use by the population.

In outdoor spaces, thermal comfort state is strongly influenced by user's satisfaction, and this factor makes the definition of comfort limits very complex to define in these environments, since it involves the understanding of the interrelationship between many different parameters (NIKOLOPOULOU, STEEMERS 2003).

According to Nikolopoulou and Steemers (2003), an analysis based only on physical parameters, used in predictive models, is not enough to describe the comfort conditions in outdoor spaces. Therefore, these authors point to the importance of the adaptive conditions (physical, physiological and psychological) in the thermal comfort sensation of the users. Among them, the psychological adaptation is of extreme importance, since the behavioral and psychological factors affect the satisfaction of the users and contribute to the existing differences between the actual sensation votes (ASV) and the thermal comfort calculated through predictive indexes.

In this context, a pilot study was developed as part of a larger study investigating whether the different levels of shading affect the thermal comfort of users and their time of exposure in outdoor spaces of leisure, in different weather conditions. It is worth noting that the relationship between thermal comfort and permanence time is still a subject rarely explored in research (NIKOLOPOULOU and STEEMERS, 2003; ALJAWABRA and NIKOLOPOULOU, 2010; YANG et. al., 2013; LIN et al., 2013; LI et al., 2016; SABBAGH et al., 2016).

## **Materials and methods**

In order to investigate the relationship between levels of shading, thermal comfort and time of exposure in the outdoor space, a pilot study was developed in the Bauru Municipal Zoo Park (Lat. 22°18'54" South, Long 49°03'39" West and average altitude of 530m), medium size city of the State of São Paulo, Brazil. The local climate, according to Köepen's climatic classification, is Aw, characterized as a tropical climate with summer marked by high temperatures and rains and mild and dry winter.

The two spaces chosen to conduct the survey have the same attractiveness and are part of the feline area (Figures 1 and 2), and have been called Subspace 1 and 2. Subspace 1 is located in front of the lion cage and has a smaller Sky Vision Factor - SVF (0,473). Subspace 2, located in front of the "jaguar" cage, has a higher SVF (0,712).

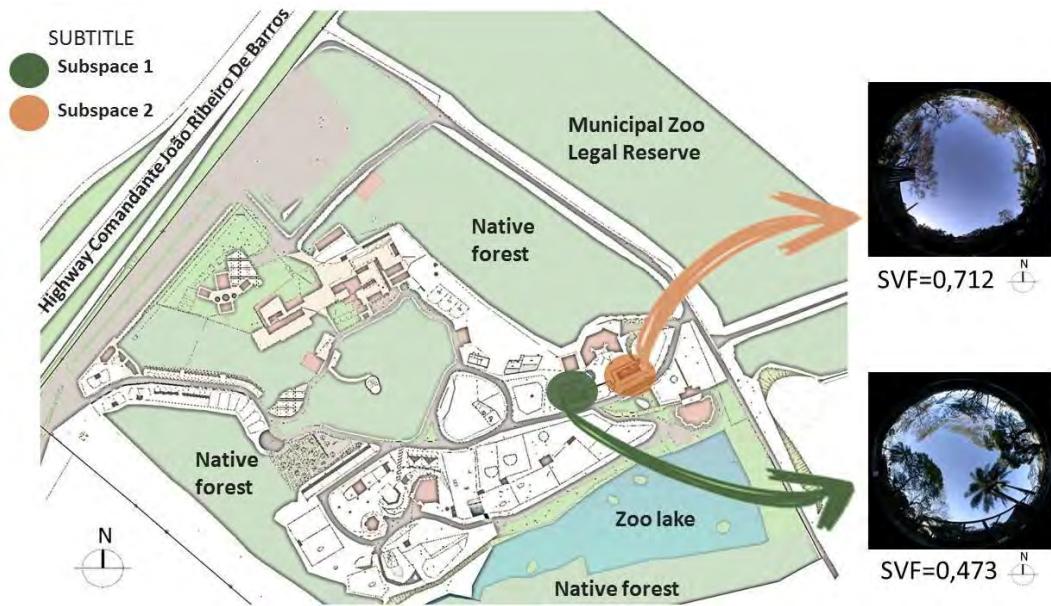


Figure 1. Internal map with highlight for the study areas and SVF. Adapted from <http://www.zoos.mono.net/upl/14646/Bauru.jpg>.



Figure 2. Areas of study.

From the choice of these subspaces, the following methodological steps were taken: image capture for SVF determination, monitoring of environmental variables, survey of activities, application of questionnaires to users, survey of climatic data and identification of comfort range. A Nikon Coolpix 4500 photo camera with fisheye converter FC-E8 was used for capturing images to calculate the Sky Vision Factor (SVF). For the monitoring of environmental variables, the HOBO H8 Pro Series was used to collect data on air temperature, globe temperature (HOBO external sensor with gray globe, built with an official ping-pong ball, painted in gray) and a direct reading thermohygrometer to collect wet bulb temperature.

Simultaneously with the microclimatic survey, questionnaires were applied, based on the RUROS Project - Rediscovering the Urban Realm and Outdoor Space (NIKOLOPOULOU; LYKOURDIS, 2006) for the identification of the Actual Sensation Vote (ASV)

of users on a 5-point scale (-2 very cold, -1 cold, 0 comfortable, +1 warm, +2 very hot), the thermal preference and thermal acceptability (comfortable, uncomfortable), and also the uses, activities developed and identification of the profile of users (gender, age group, clothing). The questionnaires were applied to a sample of 196 users (98 in each subarea), defined for a fixed user range (from 3500 to 4000 users, counting the 3 days), in which case the margin of error was approximately 10%.

The data of the meteorological variables of the field survey period were obtained at the Bauru Meteorological Center (IPMet) of the UNESP Campus of Bauru. Comfort ranges were identified through analysis of the PET index and its relationship with thermal sensation, thermal satisfaction and acceptability of users at different levels of shading (related to SVF). Users' exposure in the areas was also investigated, where photographic records were taken every 3 minutes, with a common photographic camera supported on a tripod. The field survey was performed for 3 days (02<sup>nd</sup>, 03<sup>rd</sup> and 04<sup>th</sup> of July, 2016), in the subspaces 1 and 2 (the lion and "jaguar" cages, respectively), from 10:00 a.m. to 4:00 p.m. According to IPMet, this winter period was characterized by low humidity (42.92%), and the temperature variation registered in the 3 days was of a minimum of 19.4°C (03/July at 6:30 p.m.) and the maximum of 28.2°C (on the 03<sup>rd</sup>, at 1:00 p.m.).

### **Results and discussions**

Through the analysis of the questionnaire data, it was possible to verify that 49% of the visitors are from the city of Bauru; and the majority (50.9%) says they make annual visits to the park, mainly at weekends, or during school vacations. These results reveal the importance of the zoo to the region, since the other 51% of visitors are from nearby towns. Table 1 shows the values of the users' profile, metabolic rate and level of clothing insulation.

The measurement days were characterized by the first hour with milder temperatures in the two subareas of study (Figure 3). Relative air humidity, at the beginning of the measurement, presented an average value of 71% subspace 1 and 57% subspace 2. The period from 12:00 p.m. to 01:00 p.m. on the 3 days shows higher temperatures, reaching an air temperature in subspace 1 of 29.9°C and the average relative humidity of this time of 34%. In the subspace 2, the values at this period were: average temperature of 31.5°C and average relative humidity of 27%.

Table 1- Users' profile, metabolic rate and level of clothing insulation.

GENDER	AGE	METABOLIC RATE	LEVEL OF CLOTHING INSULATION	FREQUENCY OF VISITATION
52.40% Female	31.73% 35-44 years	100% w/m <sup>2</sup>	110 60% - 0.5 clo	50.95% yearly
47.60% Male	30.29% 25-34 years		7.21% - 0.22 clo	19.71% first time
	16.83% 18-24 years		32.79% - 0.45 clo	15.87% semester
	13.46% 45-54 years			6.73% quarterly
	6.25% 55-64 years			3.37% monthly
	1.44% >65 years			1.92% every two years
				0.96% every five years
				0.49% every four months

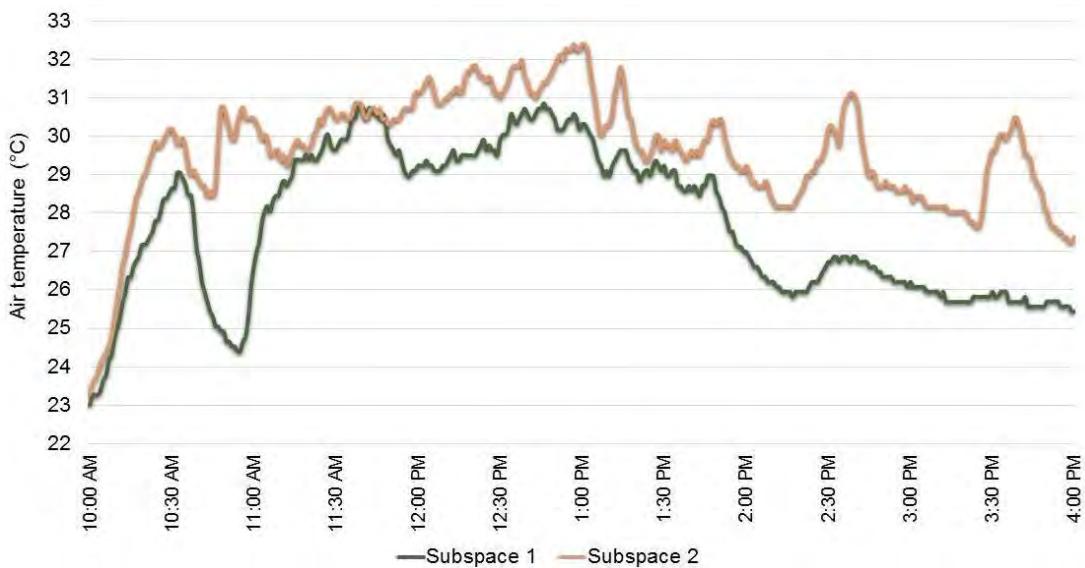


Figure 3. Average hourly temperatures of the 3 days of measurement (July 2<sup>nd</sup>, 3<sup>rd</sup> and July 4<sup>th</sup>, from 10 a.m. to 4 p.m.).

If the data collected on the subspaces were compared to those recorded by IPMet, the differences in air temperature reached 9.2°C at 12:52 a.m. of the first day of collection in the jaguar area. The air humidity in subspace 1 was higher, an average of 11% higher than the air humidity in the local Meteorological Station, whereas in subspace 2 the values were similar to those of the IPMet.

According to the questionnaire, the degree of interest of the users by these felines was similar, but the users showed little tolerance to the incidence of direct solar radiation, and therefore, the visitation period of the users to the jaguar site was shorter, due to lack of sun protection in the space.

Through the photographic records, the average length of stay in this space was less than 3 minutes, while in the lion site, the recorded time was 3 to 12 minutes. Sabbagh *et al.* (2016), in a survey conducted in Dubai, conclude that when users felt "uncomfortable", they remained no more than five minutes in the area exposed to the sun, and as a mechanism to return to the stage of "comfort" they remained a longer period in shaded areas.

An example of the records for analysis of the length of stay can be seen in Figure 4.



Figure 4. Example of records for analysis of the length of stay.

This difference cannot be attributed to the fact that one animal is more interesting than the other, because according to the questionnaires, the interest of the users by these felines was shown to be of similar degree (Figure 5), but because subspace 1 has a milder microclimate due to lower SVF.

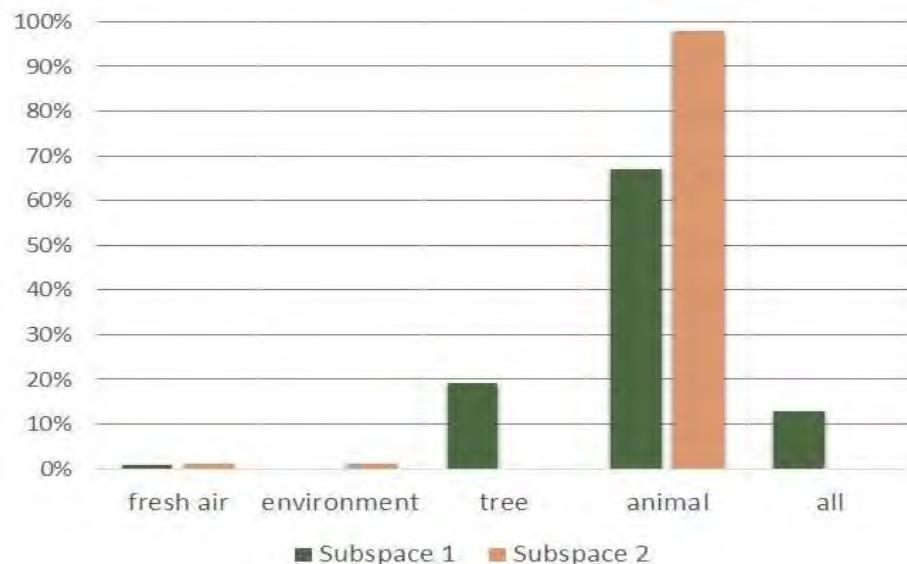


Figure 5.Location preference chart.

In subspace 1, which is shaded by vegetation and with a more pleasant microclimate, the majority of users (57.8%) showed satisfaction with the environment in general, since they felt comfortable. In the second area, the users' dissatisfaction was related to the lack of shading, where 74.8% of respondents reported as the main feature to be changed, because it directly affects the microclimate.

Figure 6 compares the thermal sensation and preference of users in the two areas of analysis.

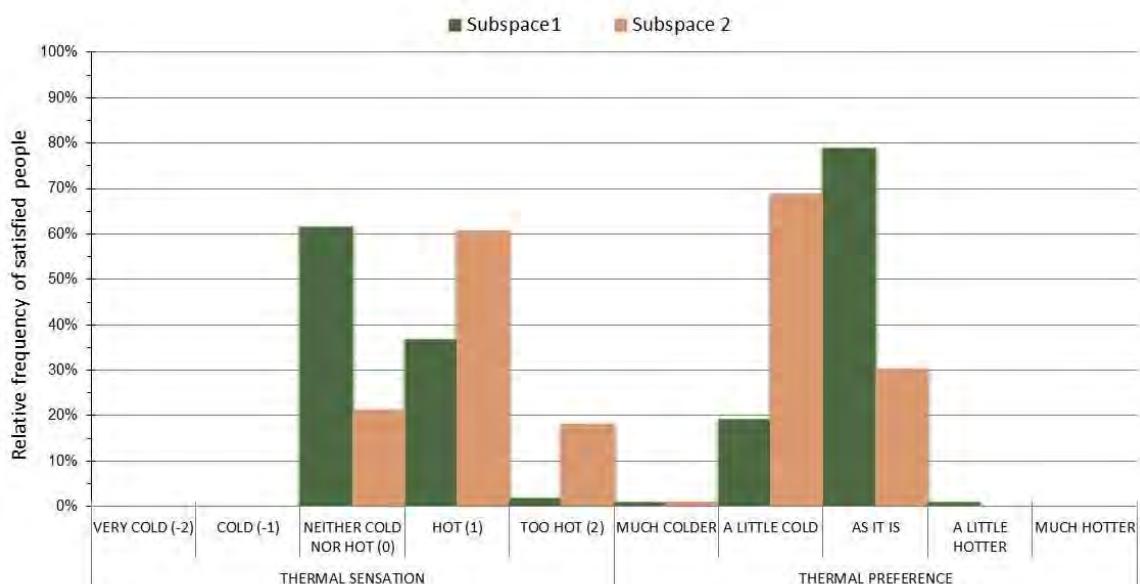


Figure 6.Comparison of thermal sensation and thermal preference of users in the study areas.

It is clear the difference reported by visitors regarding microclimate preference: in subspace 2 almost 70% of respondents throughout the day say they prefer the microclimate a little cooler, while in subspace 1 approximately 80% of users prefer the microclimate as it is. Figure 7 shows boxplot graphs for all PET temperature values grouped according to the ASV.

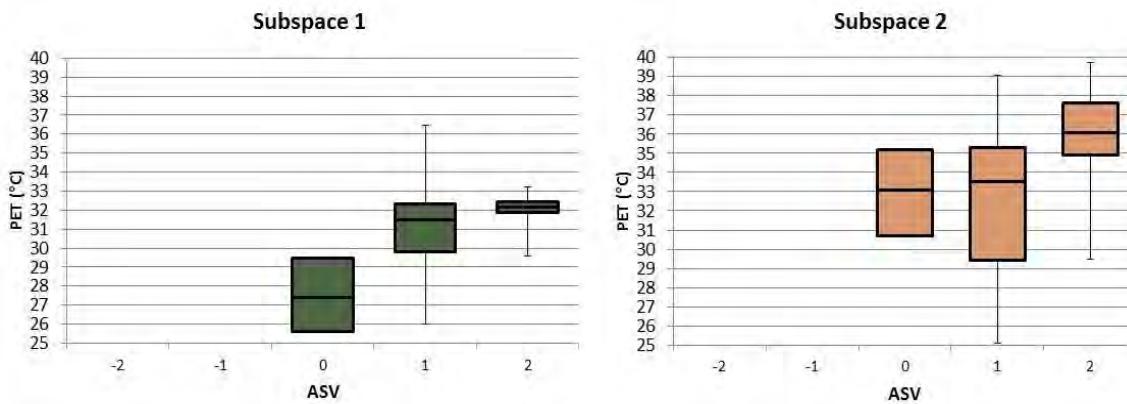


Figure 7.PET temperature range related to users' ASV ranges in subspace 1 (lion) and 2 (jaguar).

The neutrality values for the PET temperature in subspace 1 ranged from 25.6 to 29.5°C; in subspace 2 from 30.6 to 35.3°C. Referring to Figure 7, the thermal neutrality in subspace 2 is within the range of heat discomfort (+1) comprising temperatures from 24.4 to 35.4°C. Another factor observed was that although subspace 2 presented a higher percentage of uncomfortable users, the comfort limits tolerated by the respondents were greater than in subspace 1. This factor can be justified by the adaptation and tolerance of each one to comfort, which changes from person to person, and the psychological factor of satisfaction with the space where, according to Coutinho (1998), not all people have the same thermal sensation in the environment they occupy.

### **Final considerations**

The results of the research contributed to the confirmation that different levels of shading by trees, in outdoor spaces of leisure, decisively interfere in the conditions of thermal comfort and in the time of permanence of the users. Thus, the better microclimatic quality observed in subspace 1, with less SVF (Lion site), contributed to a greater percentage of comfortable people (80%) and their longer permanence time (up to 12 min) at the site. Whereas in subspace 2 (jaguar), with higher SVF, the greater thermal discomfort due to heat (75% of respondents) contributed to a reduction in exposure time (less than 3 min), due to the low tolerance of users to the direct solar incidence. It should be noted that the evaluated weather conditions were during the local winter period when air temperatures are warmer and air is drier. Therefore, the microclimatic conditions in both subspaces may be more aggravating on summer days, when temperatures are higher and relative air humidity is greater.

The research of this pilot study will continue in hot weather conditions. However, the results obtained here, in addition to highlighting the need for interventions to improve local microclimatic quality also contributed to prove the relation between thermal comfort and length of time spent in outdoor spaces, an investigation that has been little explored in the studies of the area.

## References

- ALJAWABRA, F., & NIKOLOPOULOU, M. (2010). Influence of hot arid climate on the use of outdoor urban spaces and thermal comfort: Do cultural and social backgrounds matter? *Intelligent Buildings International*, 2(3), 198-217.
- COUTINHO, A. S. (1998). *Conforto e insalubridade térmica em ambientes de trabalho*. Edições PPGEP.
- LABAKI, L. C.; FONTES, M. S. G. C.; BUENO.BARTHOLOMEI, C. L.; DACANAL, C. (2012). Conforto térmico em espaços públicos de passagem: estudos em ruas de pedestres no estado de São Paulo. *Ambiente Construído*, v. (12), n. 1, p. 167.183.
- LI, K., ZHANG, Y., & ZHAO, L. (2016). Outdoor thermal comfort and activities in the urban residential community in a humid subtropical area of China. *Energy and Buildings*, 133, 498-511.
- LIN, T.P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, (44), 2017–2026.
- LIN,T.P; TSAI, K.T; LIAO,C.C; HUANG, Y.C.(2013). Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. *Building and Environment* (59), 599.611.
- MONTEIRO, L., & ALUCCI, M. (2007). Conforto Térmico em Espaços Abertos com Diferentes Abrangências Microclimáticas: parte 2: proposição de calibração de modelos preditivos. *ENCONTRO NACIONAL*, 9, 1231-1240.
- NIKOLOPOULOU, M., & STEEMERS, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, 35(1), 95-101.
- NIKOLOPOULOU, M., BAKER, N., e STEEMERS, K. (2001). Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Solar Energy*, (70), 227–235.
- NIKOLOPOULOU, M.; LYKOURIS, S.(2006) Thermal Comfort in Outdoor Urban Spaces: analysis across different European countries. *Building and Environment*, Oxford, v. 41, n. 11, p. 1455.1470.
- SABBAGH, N. A., YANNAS, S., CADIMA, P.(2016). Improving Pedestrian Thermal Sensation in Dubai. 36th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments. PLEA 2016 Los Angeles
- THORSSON, S., HONJO, T., LINDBERG, F., ELIASSON, I., & LIM, E..M. (2007). Thermal comfort and outdoor activity in Japanese urban public places. *Environment and Behavior*, (39), 660–684.
- THORSSON, S., LINDQVIST, M., & LINDQVIST, S. (2004). *Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg*. International Journal of Biometeorology, 48, 149–156.
- YANG, W., WONG, N. H., & JUSUF, S. K. (2013). Thermal comfort in outdoor urban spaces in Singapore. *Building and Environment*, 59, 426-435.
- ZACHARIAS, J., STATHOPOULOS, T., & WU, H. (2001). Microclimate and downtown open space activity. *Environment and Behavior*, 33(2), 296-315.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Integrated Urban Regeneration and Climate Change in the Spanish Peninsular Mediterranean: The Case of the Coast of Málaga

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**Abstract:** Currently, the peninsular Mediterranean coast is the most urbanized and populated area of the country, with the Western Costa del Sol (Málaga) as a paradigmatic case, in which the anthropized surface surpasses, in some of its municipalities, 90% in its first 500m and 80% if it is advanced to 2 Km. The loss of habitats, ecosystems and their services, are the result of these urbanization processes and of their unsustainable patterns of consumption of scarce or non-renewable natural resources, with direct negative influence on the foreseeable effects of climate change on this coast, as well as on its main socio-economic activity, tourism (which also contributes to trigger this phenomenon). The objective of this research is to diagnose the initial situation and the singularities of this territory, in order to detect the main challenges and starting to outline the most appropriate strategies for their integrated regeneration, where mitigation and adaptation from the climate change would be considered. The methodology used is supported by the analysis of recent scientific production, which addresses the phenomenon of climate change in coastal areas and, from its detailed study, establishing the state of the question at hand and defining the suitable measures for the coast of Málaga.

**Keywords:** climate change, Western Costa del Sol, tourist-residential model, integrated urban regeneration.

### Introduction

As a result of the colonization process experienced by the peninsular Mediterranean coast, driven by tourism and real estate, which began in the middle of the XX century, rural territory and economy are replaced by a fragmented space, mere support of extensive tourist-residential urbanizations, accompanied by the recreational uses that these demand, generating a new economy based on service sector and construction, linked to tourism. The transition from an agricultural structure to a tourist model, led to the loss of the territory's role as a producer of food and support of resources such as water, basic for the subsistence of the population, allowing relocation and uncontrolled urban growth.

The result of the above would be the progressive filling of the first peninsular coastline in which an urban continuum is formed, where more than half of the population of this coast is concentrated in its first 2km. In this process the province of Málaga stands out in which the transformation reached 56.91% of its surface area in 2011 (Estévez et al, 2016), with the highest percentages of the coastal municipalities of the Western Costa del Sol region (henceforth WCS) (figure 1), 89% of Mijas, 86% of Benalmádena, 81% of Marbella (Villar-Lama, 2011), generating what has been defined as a linear city on a territorial scale that currently exceeds the provincial limits, entering the province of Cádiz.

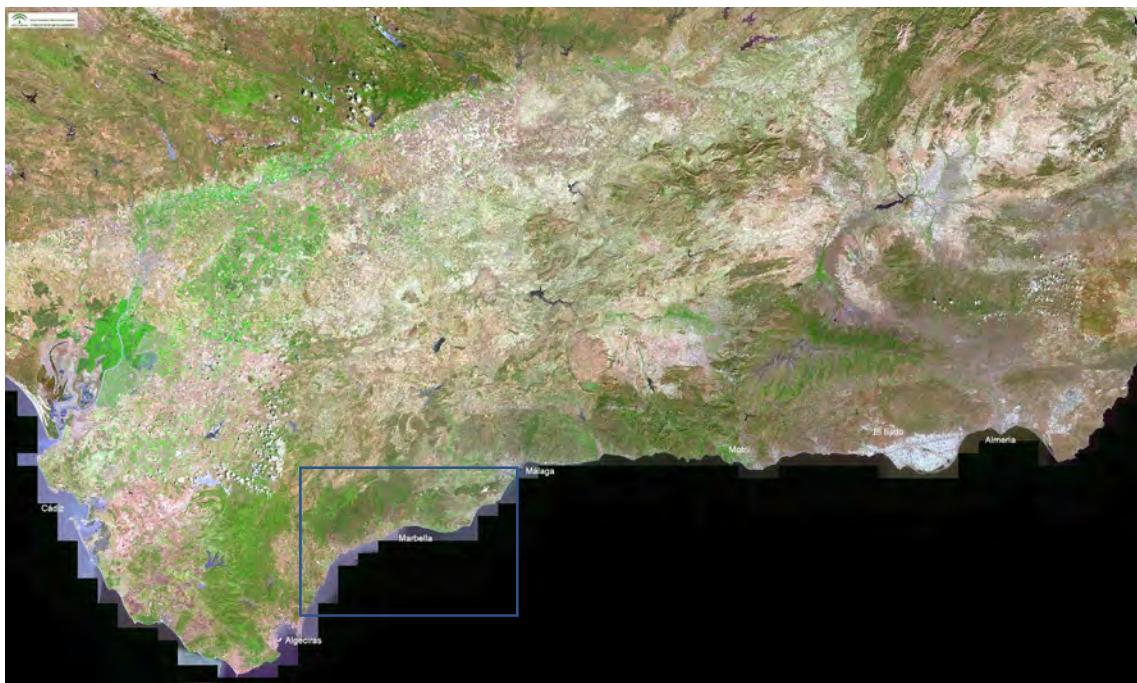


Figure 1.WCS. Andalusian Mediterranean coast. <http://laboratoriorediam.cica.es/VisorGenerico/>

Within this coastal border, the state of its first 500 m, measured from the maritime public domain on land, is particularly concerning. In which, multiple economic interests and different administrative competences converge, resulting in particular vulnerable to certain phenomena (raising the sea level, coastal regression, increased flooding due to extreme weather events, etc.) effects, all, linked to climate change.

At the tourist-real estate level, this first strip of 500 m with high scenic value generates the greatest speculative interests given its strategy value as well as for its physical proximity to the sea. Note in this regard, that the urbanisable soils included in the urban planning in force legitimise the transformation of the last vacant spaces, which paradoxically, constituting one of its main threats. On the Mediterranean coast of Andalusia, 41,60% of the area was occupied by artificial uses in 2011, while in the province of Malaga it was 74,82% (Estévez et al, 2016), however previously in 2005, the percentage surpassed in the WCS (90% of Marbella, 59% of Estepona, 91% of Mijas, 95% of Fuengirola, 90% of Torremolinos, or 85% of Benalmádena) (Prieto, 2013).

The implementation of this tourist-residential model has generated, as collateral damage, the disappearance of habitats and coastal ecosystems, wetlands, dune systems, orchards, etc., minimizing the ecosystem services of supply of water, of energy, greenhouse gases absorption, regeneration of urban waste and waste water, etc. These factors have an impact on the generation of greenhouse gases, (henceforth GHGs), responsible for the greenhouse effect that cause global warming. This phenomenon leads, in a long-term, to the changes in Earth's climate or over its weather patterns, known as global and anthropogenic climate change, whose effects on this coast are the scarcity of rainfall and with them of drinking water. The increase of the episodes of torrential rains and with them of the floods. The rise of the level of the sea, temperature increases, etc.

Lastly, this work is structured in a first section that identifies some of the main effects related to climate change in the Mediterranean coast in general, and in the Western Costa del Sol in particular. A second section analyses the urban metabolism of the WCS, which is influenced by the tourist activity, or its ecological balance, using as an indicator the ecological

footprint and the carbon footprint. Finally, the conclusions outline a set of measures, still of a general nature, to address the regeneration of this space, linked to mitigation and adaptation to climate change.

### Vulnerability to flooding and rising sea levels and their link to climate change

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment (AR5, 2013-2014) establishes, for the year 2100, forecasts of average sea level increases of between 26 cm and 98 cm, depending on the scenarios evaluated. At the same time, it announces for medium-latitude territories such as Andalusia, extreme precipitation events which will probably become more intense and more frequent. It will suppose on the Mediterranean coast Andalusian, an increase in the floods by overflowing river channels (usually short-haul and steep slopes), especially of the lower topographic level sections, closer to the river mouths.

The risk of flooding or coastal erosion due to sea level rise, as a result of the global warming component, has a special impact on those urban areas adjacent to the maritime public domain, where sediment inputs have been observed depleted by the presence of artificial protection elements, which have altered the coastal dynamics. These phenomena, in turn, hinder the evacuation of river waters, increasing the likelihood of overflowing their channels. This situation is exacerbated in the WCS case by the urban transformation of the coastline that has occupied and constrained the flood plains to extreme limits, might pose high socioeconomic damages in terms of the assets potentially affected by flooding, reducing the availability of spaces that allow the cushioning or adaptation to the rise of the sea level and increasing the sedimentary imbalance.

Given the environmental and socioeconomic deficits, resulting from the high level of territorial artificialization and flooding risk identified, in this analysis we will focus on the Western Costa del Sol, strip of coast of Málaga between Torremolinos and Manilva municipalities.

Recently, along the coastline of the WCS, 77,79km of coastline and 129km of river channels have been delimited, subject to potential significant flood risks of marine and fluvial origin (scenario T = 100 years), as well as 4,1km<sup>2</sup> with risk of marine flooding in which 8.655 inhabitants reside (SNCZI, 2016), mainly concentrated in Fuengirola, Marbella (figure 2 and 3), Estepona and Mijas municipalities.



Figure 2. Urban continuum in Marbella. WCS. Areas with Significant Potential Flooding Risk  
<http://sig.mapama.es/snczi/visor.html>



Figure 3. Las Chapas district, Marbella. WCS. Area with Significant Potential Flooding Risk.  
<http://sig.mapama.es/snczi/visor.html>

### The western Costa del Sol: Tourist activity and urban metabolism

Currently, the urban-tourist continuum of the WCS (figure 4) is made up of 48% of its extension by residential areas and golf courses (Villar-Lama, 2013). As a result of this expansive model and the absence of efficient public transportation, mobility in this environment depends basically on the private vehicle, as we know, a large consumer of energy and one of the first GHGs generators in this environment, to which there is no alternative than displacements by road, in the municipalities to the west of Fuengirola, where the railroad come to an end.



Figure 4. Western Costa del Sol Region. Urbanized area of the coast. 2011.  
<http://laboratoriorediam.cica.es/VisorGenerico/>

In this territory, the consumption of water, energy or the generation of urban waste is significantly higher than that of the traditional city, which is largely justified by the greater demand linked to tourism and, in a significant way, by the increasing presence of climatic immigrants (people who change their place of habitual residence, mainly for climatic motivations, at least six months a year) (Requejo-Liberal, 2007), from central and northern Europe. We point out that, on this coast, they are mainly of British origin, and given their patterns of consumption of natural resources and contamination by waste, adequate to those of their place of origin, they show higher rates than local ones.

### ***Water consumption and wastewater regeneration***

The growth of the population and the tourist activity, combined with traditional agricultural use, are the main reasons for the water demand of the Andalusian Mediterranean coast, especially intense during the summer period, when rainfall is practically zero, questioning the guarantee of supply of the area. These circumstances will be exacerbated by the average reduction in precipitation due to climate change of 7%, 16% and 25% in the periods 2011-2040, 2041-2070 and 2071-2100, which will lead to a decrease of 12%, 30% and 41% of the runoff, higher than the national forecast (CEDEX, 2012).

On the WCS, the narrow coastal strip between Estepona and the low river Guadalhorce, where a number of aquifers of interest are located, was once occupied by fertile farmland which, to a large extent, disappeared under the present continuous urban strip. Both of them uses continue to demand an enormous amount of water, the urban ones almost tripling in the summer periods. This is why it is used the resources generated by the marshes, the desalination plants, the regenerated waste water for irrigation, the direct water intakes of the river channels but, mainly, from the overexploited coastal aquifers, with a 59% of total resources (Gómez et al, 2001). Being even detected phenomena of marine intrusion, among those closest to the coast. This situation causes the deterioration of surface and groundwater, which also endangers the maintenance of ecosystems.

At the beginning of the first decade of the 21st century, the volume of demand for annual water in the WCS amounted to 187,44hm<sup>3</sup>, the main percentage was allocated to the urban supply with a 56,17% of the total (25% destined to the residential urbanizations), a 3,18% to irrigation of golf courses, and the remaining 40,65% to agriculture (Natera-Rivas, 2005). Human consumption has remained practically constant in that decade, accounting for 113,15m<sup>3</sup> per inhabitant per year (309,6liters per inhabitant per day) in 2009. This level of consumption is unsustainable, being well above the already high 247liters per inhabitant and per day, recommended according to the Hydrogeological Atlas data, for the Province of Malaga (Jiménez-Madrid, 2014).

Thus, the WCS is considered as one of the most unbalanced areas in terms of demand and water resources of the province. The overexploitation of its aquifers is alarming and it is joined by lower than average rainfall in recent years, questioning the guarantee of supply if the dynamics of growth of urban demand go on (which is derived from the increase in population, and the standard of higher consumption among tourists and climatic immigrants). To address this water deficit, the reuse of regenerated water in waste water treatment plants (henceforth WWTPs), as water for irrigation has been proposed. Along this line, between 2001 and 2003, about 3Hm<sup>3</sup> per year were used for irrigation of golf courses, which meant scarcely between 5% and 7% of the total purified water (Miranda-Páez, 2005). Currently, almost 20% of the total volume of purified water is destined to irrigate 34 of the 43 golf courses in the area (which has risen alarmingly in recent decades). To the still insufficient

reutilization of the reclaimed waters, there is also the added necessity of resizing of the WWTPs, which work above its capacity, surpassed by the continuous population growth.

### ***Generation of waste and electricity consumption***

In 2014, urban waste generation in the WCS amounted to 304.664 tonnes and electricity consumption reached 2.254.558MWh (53,3% in the residential sector and 33,4% in the commercial services sector) (MADECA, 2015). Based on the population census, 519.769 inhabitants (29,0% foreigners) as of January 2014, establishes a production of 586,15kg of urban waste per person, and a consumption of 2,31MWh of electricity for residential use, much higher than the 487kg of waste or the 1,33MWh consumed per resident in the municipality of Málaga, which is basically justified by the higher standard of consumption of tourists and climatic immigrants. In the case of waste, the figures also question the efficiency of local recycling and reuse measures.

### ***Ecological balance***

Adopting the ecological footprint as an indicator of the sustainability of human behavior over its territorial environment, the Western Costa del Sol reaches 4,6537 hectares per inhabitant (compared to the Andalusian average of over 3,5hectare per inhabitant), according to the population data and the demand for resources of the year 2000. The bioproducing area needed to attend to it, would be 24,16 times the total area of the coastal municipalities, identifying a situation of clear ecological deficit (Cano-Orellana, 2007).

Upon analysis of the carbon footprint, in order to determine the total amount of GHGs produced as a consequence of human activity, between 2000 and 2013, the average of emissions in the coastal municipalities amounted to 1.365.513Tons of CO<sub>2</sub> equivalent, and the sink capacity of 15.163Tons of CO<sub>2</sub> equivalent. For the purpose of comparison, in Malaga capital, emissions and carbon sink capacity amounted to 2.085.354 and 14.728Tons of CO<sub>2</sub> (REDIAM, 2015) equivalent, more than 1,5 times the emissions of the municipalities of the WCS, for a very similar carbon sink capacity.

This huge imbalance between emissions and absorption frees virtually all GHGs generated in this environment, mainly by road traffic, electricity consumption, waste treatment and wastewater. The reduced capacity of the coast as a sink for these gases derives from the deep artificialization of the coastal strip, with the consequent scarcity of arboreal masses and free soil, which are principal in charge of this function. This situation could be extensible to most of the municipalities along the Mediterranean coast of Andalusia.

Thereby, for the period 2000-2008, coinciding with the last real estate bubble in Spain, the carbon footprint of some municipalities of the WCS stands out, concretely, 6,08 Tons of CO<sub>2</sub> equivalent per inhabitant in Marbella, 4,6 in Mijas, or 4,5 in Torremolinos (Jiménez-Madrid, 2014).

### **Conclusions**

Currently, the peninsular Mediterranean coast is the most urbanized and populated area of the country, with the Western Costa del Sol (Málaga) as a paradigmatic case, in which the anthropized surface surpasses, in some of its municipalities, such as Marbella or Mijas, a 90% in its first 500m and a 80% if it is advanced to 2 Km. In spite of the excessive levels of urbanization reached, of the large number of existing vacant or secondary dwellings (which total 148.015 units in front of the 194.398 main houses, data from 2011) (MADECA, 2015),

and the potential risk of flooding due to rising sea levels, a large part of the vacant spaces is exposed to a possible, and legal, transformation into new urban land.

The fruit of this tourist-real estate activity, in the Costa del Sol region the population growth has remained practically constant since its origin, being difficult quantifiable the real population since to the population census, which currently exceeds half a million inhabitants. Beside, people who are not registered as residents, but residing in this coast, should be added. Inside of this group a growing number of climate immigrants could be include, as well as the seasonal population formed by tourists, thus exceeding one a million of real inhabitants during the summer months. In this respect, referred to 2003, The Regional Planning for the WCS (annulled in October 2015) had estimated 616.314 inhabitants as real population figures (facing only 290.200 residents registered) and, with the floating resident population, mainly tourists, would have reached close to one million inhabitants.

The result of these processes and unsustainable patterns of consumption and behavior (the ecological deficit and the GHG emissions of the municipalities that make up this coast prove it) are the loss of habitats and ecosystems as well as the deterioration of regulation or supply services, or cultural activities, that they provide. They call into question the guarantee of water supply and even of energy, the management of waste or the maintenance of their cultural heritage, due to the carrying capacity of this territory has been amply exceeded, especially during the peak time summer.

In addition to the disappearance of habitats and coastal ecosystems, the foreseeable effects of climate change on this coast, above described, have a direct and very negative impact on the quality of life and human health, as well as on its main socio-economic activity, tourism, which is especially vulnerable to the scarcity of rainfall and with them of drinking water; the rise of the level of the sea; and temperature increases. Phenomena, which in turn contributes to trigger, given that 5% of total global CO<sub>2</sub> emissions came from tourism, a 75% corresponds to transport (AR4, 2007).

In this regard, a sustainable tourism activity requires mitigation strategies such as revaluing and fostering proximity in the choice of destinations, as well as prioritizing the reduction of energy consumption, the efficiency, and betting on energies coming from renewable sources, especially in air transport and its low-cost format, which is the most responsible for GHG emissions linked to tourism. At the institutional level, the efficient use of airspace and thereby the reduction of fragmentation, or the establishment of emission rates, are some of the measures tested at EU level. Lastly, regarding to companies linked to tourism, *they must establish a code of good practices that include environmental planning criteria and predisposition to the application of regulatory measures, and be involved in the management of the destination* (Valls y Sardá, 2008).

*It can be concluded that the integrated regeneration of this space, must go hand in hand with the real awareness of the political class about the need for a change of the urban model of consumption in order to reduce its ecological footprint, of the citizen participation, and linked to the fight against climate change. Specifically:*

With the adoption of mitigation measures, on which the sustainability of tourism will depend, reducing the consumption of water and energy; promoting the generation of renewable energies; recovering and renaturalizing the coastal edges and the river channels, restoring their public character in cases in which they have lost it. Adapting buildings and its surroundings to the physical environment, with the use of bioclimatic strategies, the reduction of impermeable surfaces, the increase of green spaces, etc.

Identifying adaptation measures aimed at the protection and recovery of the coast and its ecosystems, beaches and dunes, traditional agricultural spaces, with the reintroduction of arboreal masses, etc.

With the adoption of protection, regulatory and planning measures, for the risk areas, in order to avoid the impacts caused by flooding; reducing the exposure of cultural and built heritage; modifying land uses, limiting new urban developments, and anticipating the progressive withdrawal or adaptation of existing buildings.

Integrated Coastal Zone Management (ICZM) with a supramunicipal vocation (in which all the agents with an interest in this coast participate in a coordinated way, and with the citizens playing a preferential role), would facilitate the successful implementation of these strategies against climate change, to be applied to the peninsular coastal strip of the Mediterranean and, particularly, to the WCS, strongly anthropized, favoring its integrated regeneration

## References

- Cano-Orellana, A. (2007). Huella Ecológica Local: El Caso de los Municipios del Litoral Andaluz. *Estudios Turísticos*, 172-173, pp. 121-129.
- CEDEX (2012)."Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua". Ministerio de Fomento.
- Gómez-Gómez, J.D., López Geta, J.A. & Navarro, J.A. (2001). Modelo de uso conjunto de recursos hídricos en la Costa del Sol Occidental. *Las caras del agua subterránea*, Vol. 2, pp. 745-752.
- Estévez, R., Prieto, F. & Alfonso, C. (2016). "Informe Cambio en la ocupación de la Costa 2016". Observatorio de la Sostenibilidad. OS. Retrieved from: <http://www.observatoriosostenibilidad.com/>
- "Fourth Assessment (AR4)". Intergovernmental Panel on Climate Change, 2007.
- "Fifth Assessment (AR5)". Intergovernmental Panel on Climate Change, 2013-2014.
- Jiménez-Madrid, A. (2014). "Dictamen Medio Ambiente y Sostenibilidad en la Provincia de Málaga". II Plan de Actuaciones Estratégicas Provincia de Málaga. Retrieved from: <http://www.fundacionmadeca.es/images/pdf/Dictamenes-Plan-Estrategico/sostenibilidad-medioambiental.pdf>
- MADeca (2015)."Información Comarcal. Costa del Sol Occidental". Observatorio Socioeconómico de la Provincia de Málaga.
- Miranda-Páez, E. (2005). Saneamiento Integral de la Costa del Sol: El permanente desafío. *Aqua Nostra, Agua de Todos. El Agua en La Costa Occidental Malagueña*, pp.74-82.
- Natera-Rivas, J.J. (2005). Agua y Poblamiento de la Costa del Sol Occidental. *Aqua Nostra, Agua de Todos. El Agua en La Costa Occidental Malagueña*, pp. 15-61.
- Prieto, F., Murray, I. & Farinós, J. (2013). "Costas Inteligentes. Visión para un Futuro Sostenible en 2030". Greenpeace, pp. 1-319.
- REDIAM (2015). "Evolución de emisiones de CO<sub>2</sub> y Huella de Carbono en Andalucía". Retrieved from: <http://laboratoriorediam.cica.es/huellacarbono/index.html>
- Requejo-Liberal, J. (2007). Turistas: del Concepto Legal a la Compleja Realidad del Actual Panorama Español. *Estudios Turísticos*, 172-173, pp. 147-156.
- SNCZI (2016). Área Riesgo Potencial Significativo Inundación. Sistema Nacional de Cartografía de Zonas Inundables. Retrieved from: <http://sig.mapama.es/snczi/visor.html>
- Villar-Lama, A. (2011). *Territorio, Turismo y Paisaje: El Proceso de Urbanización en el Litoral de Andalucía. El Papel de los Campos de Golf*. Geografía Física y Análisis Geográfico Regional. Universidad de Sevilla.
- Villar-Lama, A. (2013). La mercantilización del paisaje litoral del mediterráneo andaluz: El caso paradigmático de la Costa del Sol y los campos de golf. *Revista de Estudios Regionales*, 96, pp. 215-242.
- Valls-Giménez, J.F., Sardá-Borroy, R. (2008). Percepción de los Expertos sobre las Implicaciones del Cambio Climático en las Regiones Turísticas Euromediterráneas. *Revista de Análisis Turístico*, 5, 1er semestre 2008, pp. 46-65.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Productive Landscaping in Urban Built Environment

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**Abstract:** Recent changes in the global climate pattern has witnessed increase in unusual rains and shifting weather patterns increasing the risk of food security. The demand for food in high density living areas is increasing the energy consumption for the transportation leading to higher carbon footprint. Moreover, in tropical countries like India where extreme weather conditions exist with summers being too hot and heavy rains flooding the cities during monsoons, the increase in concrete built forms and surface simplification are leading to the Urban Heat Island effect resulting in rise in local temperatures further increasing the energy consumption in built spaces. In this scenario, roofs with green vegetative covers act as good insulation while using waste water, gives a triple fold solution of maintaining air quality, reducing energy consumption and creating an alternative for food security by providing sustainable design solutions for multiple problems of urbanisation. In urban areas where land is one of the scarce resource, there is extensive potential for application of productive landscaping in cities, not only on land but also in the building components such as rooftops, fences, walls, balconies, property setbacks, etc. that adds a green envelop to these building components. In this paper we would be exploring the possibilities of integrating productive landscaping into urban design and built environment to achieve sustainable design solutions.

**Keywords:** Productive landscaping, urban agriculture, sustainable landscaping, food security, composting

### Introduction

The urban population in India is expected to grow to 404 million by 2050 (World Urbanisation Prospects, 2014) (See Figure 1). Many of our cities are ill equipped to handle such large-scale expansion.

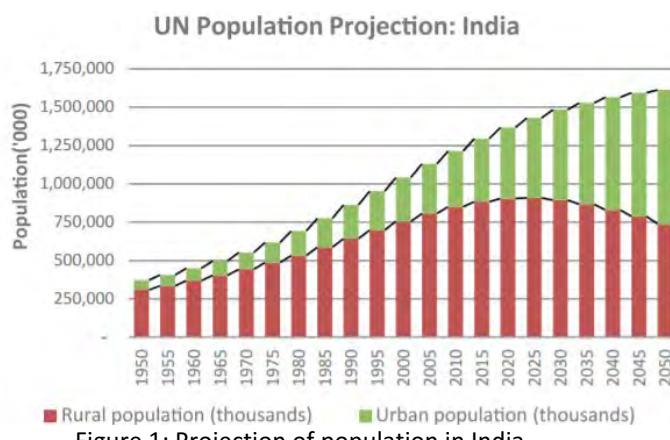


Figure 1: Projection of population in India

Resources are always limited and in a developing and highly populous country like India, resources are even scarcer. Population explosion results in the shortage of even the most basic resources like food.

## **Background: Issues and challenges of urbanisation**

There are a number of environmental, economic and social issues that are associated with urbanisation which needs to be studied and solved with a sustainable approach.

### **Environmental issues**

Climate change along with the El Nino effect, are expected to increase the frequency and intensity of current hazards, an increased probability of extreme events, spur the emergence of new hazards and vulnerabilities with differential spatial and socio-economic impacts. This is expected to further degrade the resilience and coping capacities of poor and vulnerable communities, who make up from a quarter to half of the population of most Indian cities (Satterthwaite, 2006). Hundreds of millions of urban dwellers in the Indian cities are at risk from the direct and indirect impacts of climate change. Without effective adaptation to climate change there will be very serious consequences for the most people residing in the cities in India.

Various climate models developed so far indicate following issues that would impact the cities (Bhat GK Raghupathi et.al. 2013)

- Temperature increase and higher variability leading to
  - Reduced comfort levels over longer periods across seasons
  - Increase in energy use for space cooling and heating
- Precipitation changes leading to
  - Drought, and extreme precipitation events
  - Changes in river hydrology causing floods, seasonal water scarcity
  - Cyclonic storms, storm surge and coastal flooding
- Heat island effects along with regional temperature increase
- Increasing demand of resources due to urbanisation i.e. for water, food, energy etc. leading to stress on urban ecosystem.

Since both urbanisation and climate change impacts are expected to simultaneously roll out in the coming decades, cities now are at a higher risk to the increasing severity of climate change.

### **Economic issues**

Mckinsey Global Institute (MGI) published a report “India’s Urban Awakening: Building Inclusive Cities, Sustaining Economic Growth” based on econometric model. During 2010-2030, urban India is expected to create 70 per cent of all new jobs in India and these urban jobs are expected to be at least twice as productive as equivalent jobs in the rural sector. If this demand is not met, both urban and rural areas are likely to face serious employment crisis.

Urban poor generally spend the major share of their earnings on food. Since the demand of food is higher in the cities, the cost of food is also higher making it harder for the Urban poor to meet their food needs. Poor urban dwellers, being largely net food buyers and depending mostly on markets for their food supplies, are particularly vulnerable to adverse food price shocks, and are consistently the group in society that suffers most from higher food prices. (See figure 2)



Figure 2: Diagram explaining the social, economic and environmental issues of urbanisation

### Social issues

In urbanisation, we see a constant influx of people from the rural areas in search of employment. Overcrowding of cities lead to a constant problem of scarcity of houses in urban areas leading to more and more slums. Impacts of inadequate housing conditions and basic amenities are an intricate issue involving variety of exposures that are physical, chemical, biological and social leading to various health and social issues. Increase in food prices make the urban poor the most vulnerable group to the necessity of food and nutrition. Food contamination is one major problem that takes a toll on the health of the whole urban population. Moreover, the environmental impacts of urbanisation like increase in temperatures, air and water pollution, lack of breathable air, etc. have serious effect on the health and wellbeing of the city dwellers.

### Productive landscaping as a solution to the many problems

As discussed in the earlier section, to meet the global challenges of the 21<sup>st</sup> century like urbanisation, climate change, food crisis, water crisis etc., we need to progress towards development with efficient use of available resources understanding the symbiotic relationship between urban planning, architecture, infrastructure, landscaping etc., for a culturally, economically, and environmentally productive urban realm. A one point solution to these many challenges is sought out to be urban agriculture. As quoted by Thomas Jefferson, "Agriculture is our wisest pursuit, because it will in the end contribute most to real wealth, good morals, and happiness."

The concept of kitchen gardens and localised food production is not new to the households of Indian sub tropics. It is an ancient practice where every household had some food producing plants and trees which were used for their own consumption and the excess produce was distributed in the neighbourhood. This practice also helped in maintaining the biodiversity of the region and have cleaner and healthier living conditions. However, overtime this practice became less with the cities becoming crowded and congested and the gardens being replaced by lawns and decorative plants. We reached a point that the current generation living in the cities think that growing their own food is not possible in the cities or they are not aware of how to do that.



Figure 3: Diagram explaining how productive landscaping is a solution to the issues of urban areas

Small scale and localised food production is possible in the backyards, gardens, lawns, balconies, indoors, roof tops, window sills and even walls. The major difference between rural and urban agriculture is that, in case of urban agriculture, the consumer is the producer so their production is made specific to their need which reduces waste. Urban agriculture will help the city to adapt to climate change and reduce its ecological foot print. Growing food in urban areas contribute to disaster risk reduction and adaptation to climate change by reducing runoff, reducing urban temperatures, sequestering CO<sub>2</sub>, while growing fresh food close to consumers reduces energy spent in transport, cooling, processing and packaging, whilst productive reuse of urban organic wastes and wastewater (and the nutrients these contain) reduces methane emissions from landfills and energy use in fertilizer production (See Figure 3).

Productive landscaping can also be socially productive. Urban farming provides employment to the city's slum dwellers. Urban farming also facilitates women empowerment, because women have a higher potential of becoming urban farmers as this activity can often be more easily combined with their other tasks in the household. Having community farms and community kitchens headed by women will make the process of food production, preparation and sale of healthy meals to the working community more streamlined and help them become entrepreneurs in the healthy food business. Community involvement in producing food will enhance the social fabric of the region as working together on something productive to the environment and themselves will give the urban farmers a sense of achievement through self-sustainability and unity. The activity involved such as watering and pruning also provides an individual some physical and/or psychological relaxation. Urban farms may also act as recreational areas for people to take walks, pick up fruits, buying fresh produce, educating children about how nature works by bring them in contact with farming, getting them involved in the farming activity etc.

Urban agriculture is a solution to reduce urban poverty, provide food security, decrease the dependence on food imports, and improve the quality of the food with sustainable practices. The importance of urban farming is increasingly being recognised by international organisations like UNDP, UN-Habitat and FAO (World Food and Agriculture Organisation) etc., however it is not widely practiced in India because of lack of know how. It is hoped that this paper will prove the importance and provide guidelines for the wider adaptation of productive landscaping in the urban built environment.

### **Methodologies for incorporating productive landscape in urban areas**

The main challenge with urban agriculture is the availability of land for cultivation. Therefore, we need to incorporate productive landscaping into the urban fabric where ever we have the possibility. Productive landscaping can be incorporated into the urban fabric at various scales: at building, street, neighbourhood and city levels. The potential and various design methodologies in maximizing the usage of the space are explained below:

- Productive Streets
  - Shared spaces /common spaces can be maintained by the communities at neighbourhood level
    - Use of fruit bearing trees instead of ornamental landscaping
- Areas in communities where land is available - vacant plots and large open spaces
  - Creating urban food forests in open spaces
    - Enrichment of contaminated soil using leaf litter from parks, avenue plantations, kitchen waste, etc., that can be converted to compost and used improve soil quality.
    - Softening the soil – modification to make it suitable for farming
    - Dig trenches for water percolation
    - Multi-layered diversified plants which increases the resistance towards pest attacks and natural disasters. Plants will be mutually benefit from the companionship compared to mono-cropping. This also requires less water because of high dense planting pattern there will be less evaporation from the soil (See Figure 4).
    - Mulching from the weed on site and dried leaf litter will retain the water in the soil for longer reducing the demand on irrigation.
- Areas in communities where land is a constraint – small spaces and building elements
  - Small spaces around houses and buildings
    - Replacing lawns with productive landscaping – Space can be optimised by going for modular units that can be multiplied as per the space availability (See Figure 6)
    - Use of vertical garden units where there is space constraint
    - Use of hanging pots
  - Rooftops
    - Reuse containers such as paint cans, water cans, buckets etc. to grow plants (See Figure 7)
    - Grow plants in plastic grow bags or used cement bags which are lightweight that do not add extra weight to the roof.
    - Creating raised soil beds on roof.
    - Use of vertical units using PVC pipes (See Figure 5)

- Balconies/Window sills
  - Can grow food producing plants such as green leafy vegetables, tomatoes, eggplant, okra etc in potted plants or grow bags
  - Use of vertical farming units
  - Use of hanging pots to grow food.
  - Use of balcony grills to grow climber plants.
- Walls
  - Climbers along the walls with support meshwork
  - Containers attached to wall
  - Use of trellises

Growing medium where soil is not available in abundance

- Use of Cocopeat
  - Naturally available material at affordable cost in Indian cities
  - Lightweight, so it can be used for balconies, window sills, terrace farming, green walls etc.
  - Because of the fibrous structure the moisture retention capacity is higher compared to the soil
  - It is loose which allows the plant root system to expand freely resulting in more healthy and productive crops
  - Adding vermi-compost will enhance the productivity of cocopeat medium
- Use of water for growing food (Hydroponics)
  - There is a high demand of water in urban areas therefore, we can use gray water (from kitchen, shower, sink, washing machine etc.) that is treated to the usable standard using simple mechanical process.
  - Collecting rainwater for irrigation of crops will reduce the burden on municipal sewage system.
  - Wetland crops can be grown along water streams and lakes
  - Water consumption can be reduced by going for polycropping instead of monocropping
- Improving the quality of the soil through composting organic material
  - With the process of composting we can convert the organic kitchen waste, dried leaves, grass clippings, wood waste, waste paper and cardboard into humus which increases the nutrients in the soil.
  - Adding earthworms or effective micro-organisms during the process of composting will further enhance the nutrient value in soil.

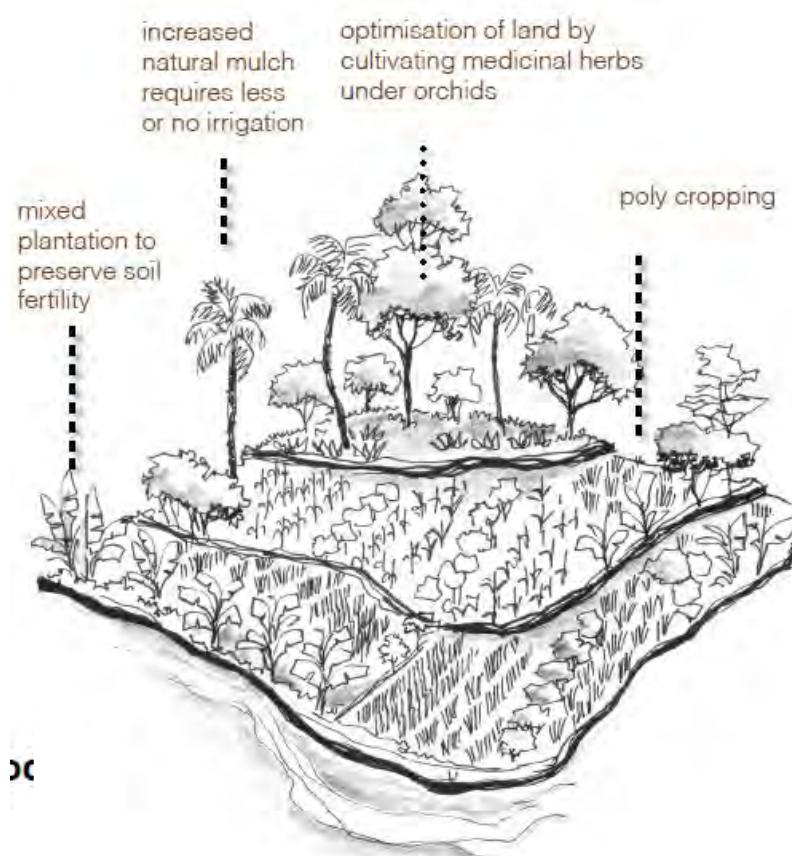


Figure 4: Diagram showing multicropping techniques for urban farming on vacant lands.

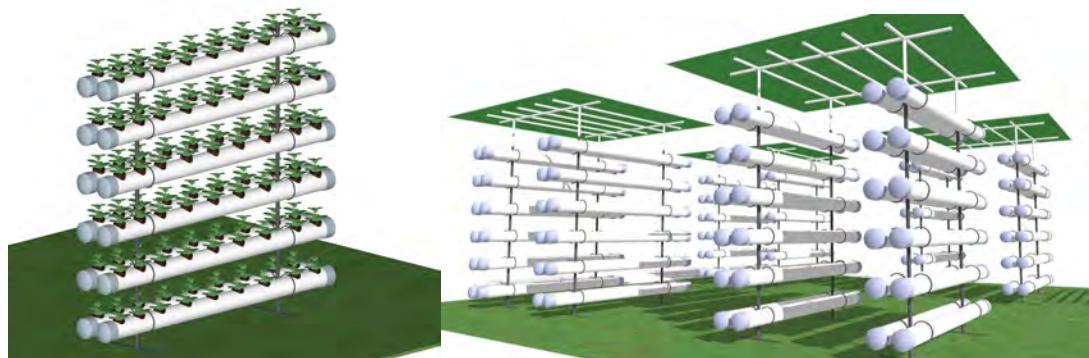


Figure 5: Vertical farming units made of PVC pipes that could be used to grow food.



Figure 6: Modular units containing a base and grow bags that can be used on the rooftop

	
Terrace garden with edible plants in Visakhapatnam, India	Use of open areas for growing food in Visakhapatnam, India
	

Figure 7: Showing the urban farming practices by few individuals in Visakhapatnam, India

## Conclusion

Local food production plays a large role in creating self-sufficient communities that are not dependent on food imports or on food that has travelled by road across the country. Productive landscaping, therefore is a holistic solution to our dependency on oil, energy consumption, carbon emissions in food transportation, reduction of urban heat island, health and economy. However, for large scale deployment of productive landscaping, we need the active involvement of the city dwellers and the local municipalities for creating conducive environment for production of food. Training and support services need to be provided for the enthusiastic urban farmers for wide deployment of productive landscaping. Further study is intended to be done on the economics and energy saving potential of productive landscaping in urban built environment.

## References

- UN 2014, World Population Prospects 2014, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, Available: <http://esa.un.org/unpd/wup/CD-ROM/Urban-Agglomerations.htm>, Accessed 12/4/2017
- Satterthwaite, D. (2006). Climate Change and Cities, London, IIED
- MGI (2010), India's Urban Awakening: Building Inclusive Cities, Sustaining Economic Growth. The McKinsey Global Institute
- Bhat GK Raghupathi, U Rajasekhar and Karnath A 2013, Urbanisation, Poverty, Climate Change: A synthesis Report – India, Gurgoan, India: TARU Leading Edge and ACCCRN



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Correlation between air-conditioning usage and peak demand of electricity from Libyan homes

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**Abstract:** Libya is a notable example amongst countries that use fossil fuels to generate electrical power in the world. Electricity in Libya is heavily consumed through the use of residential air conditioning, which comprises 36% of the total electricity generated at peak times on a hot summer day. In order to gain a general appreciation of electricity demand from cooling in Libyan domestic residences, a questionnaire was designed, comparing energy consumption and air-conditioning usage. This paper is based on the compilation of responses from the conducted survey. The questionnaire produced in this study, with 724 respondents, comprised of ten questions including building type, the number of air conditioning units used, the size of properties, and number of occupants. Moreover, the survey gave an indication of locations and the time at which air conditioning was used during the summer days , the result shows that houses with one and two storeys make up 61.3% of all housing types, meaning that the majority of Libyan people live in such buildings. Additionally the results show the impact of extreme use of air condition to the total electricity generation and the relation between the rate of increase of consumption and installed capacity of Libyan electricity.

**Keywords:** Libyan homes, Energy consumption, air-conditioning usage, Libya climate

### Introduction

In Libya, the climate is hot during summer time, so the need for cooling systems in summer are certain, especially in the southern region and coastal areas where the humidity is high. (El Bakkush et al., 2015). In the summer months, over 80% of buildings are using air-conditioners frequently within small volumes (Suleiman, 2011).

Local climate conditions have taken little notice due to cheap fossil fuel consumption in the country. As well as the introduction of mechanical air-conditioned technologies, the issue has gone out of hand concerning the environment. Energy consumption to allow comfort in buildings to be maintained cool has been huge.(Ahmad et al., 1984)

In the past, traditional buildings provided a relatively acceptable thermal comfort in winter and particularly in summer. These buildings are naturally ventilated and have a high thermal capacity. They are also equipped with a courtyard. However, in the present day the development of “modern” construction has been very fast with less care paid to the thermal quality of the buildings. Many recent buildings are not equipped with thermal insulation, and air tightness is very poor due to the lack of appropriate standards (Akair, 2007 p45).

According to the Libyan Housing and Infrastructure Board (HIB), Libya does not have its own specific criteria for housing construction, so the USA and British codes are used instead. These codes are seen as unsuitable for the Libyan climate and people's behaviour (AECOM, 2009). Furthermore, Suleiman (2011, p1928) stated that “there are no specific

energy conservation building codes to promote energy efficient buildings in Libya; however, there are some universal rules to implement energy conservation and environmental issues". Therefore, to reduce the electricity consumption in the residential sector and to increase the network efficiency, there is a need for adopting innovative technology approach in order to address these issues from an architectural perspectives (Roaf, 2012).

The objective of this study is to explore Libyan people's electricity consumption behaviour in conjunction with the housing occupancy and house type and design. Such information will be used to help investigate the correlation between air conditioning and peak electrical load in the Libyan residential sector.

### **Current Status of the Libyan energy**

The General Electricity Company of Libya (GECOL) was established in 1984 and it is responsible for all electricity sectors in Libya, including generation, transmission, distribution, and customer services.

Domestic energy use, which depends on multiple factors such as family size, lifestyle, the environment (location and climate), types of appliance in use, ownership, physical features of the house and human behaviour (Saleh et al., 2014), accounts for about 36% of the total energy consumption in Libya.

Air conditioning systems consume more energy than any other devices used in building services, and account for about 10-20% of the total energy consumption in developed countries (Alghoul, 2017). In Libya, about 18% of domestic energy consumption is used for temperature control in residential buildings, which amounts to approximately 6% of the total energy of all sectors. Hence, reduction in energy requirements by Heating Ventilation and Air Conditioning systems in buildings may lead to improved and more efficacious energy saving in buildings (Alghoul, 2017).

### **Generation annual growth**

According to the 2010 GECOL report, the country had 8,347 MW of installed capacity. Total generated energy was approximately 32.6TWh. With annual growth at 7.6%, this illustrates an average annual growth since 2003, as shown in Figure 1 (GECOL, 2010)

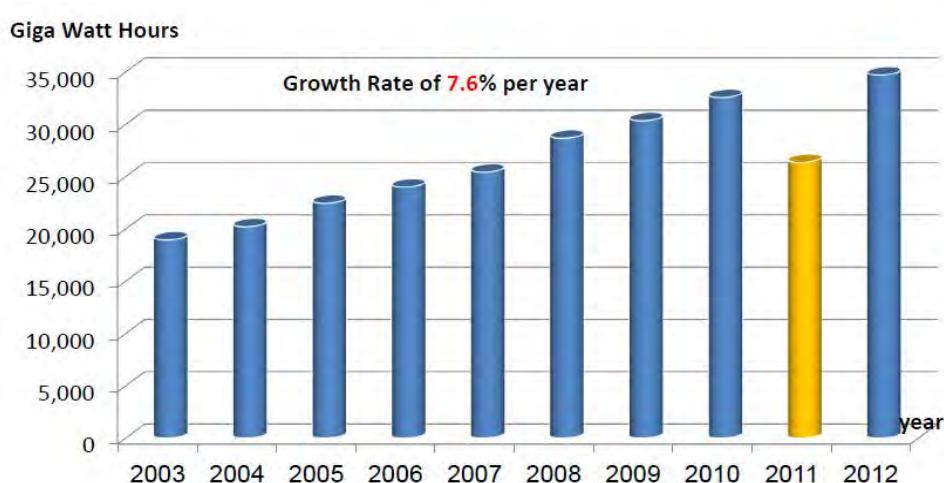


Figure 1. Energy production development 2003 – 2012 in Libya

Adopted from Current status of the Libyan power system and its future plans Power point presentation<sup>1</sup>

<sup>1</sup> [http://www.energyafrica.de/fileadmin/user\\_upload/Energy\\_Africa\\_13/Presentation\\_GECOL\\_Ashaibi\\_PAnel%204a\\_7th%20German-African%20Energy%20Forum.pdf](http://www.energyafrica.de/fileadmin/user_upload/Energy_Africa_13/Presentation_GECOL_Ashaibi_PAnel%204a_7th%20German-African%20Energy%20Forum.pdf)

The use of electrical energy in Libya is growing at a rapid rate. This growth in energy consumption is a result of the increasing urbanization occurring in the region, which is accompanied by an expanding population size, economy and degree of industrialization. Data collected over the last ten years in Libya has shown an increase in electricity consumption every year. By 2050, the government of Libya is expected to face more pressure to meet demands for the energy supply, especially in the residential sector with its cooling and heating needs. In the future, for these reasons, they must explore more efficient methods of energy use to overcome the increasing energy cost (Saleh et al., 2014).

### ***Type of Dwelling in Libya***

The Public Commission for Health Care Planning in Libya through Multi Indicator Cluster Survey (MICS) has reported that 65.4% of Libyan residents live in a one-storey house (MICS, 2003), many of which were constructed in the absence of technical data on the building materials (Suleiman, 2006). Another study by Dagdag and colleagues (2015) found that the majority of Libyan houses tend to be two- or three-storey buildings, consisting of about five rooms, and having flat roofs.

Typical construction materials include limestone bricks covered by plaster to form the external walls, and ground soft soil and marble tiles for the ground floor (Suleiman, 2011). Most use concrete and a small number use tiles, while those living in rural villages may resort to using materials such as fibre (Dagdag et al., 2015).

Installation of air-conditioning systems in the houses is a common feature due to the extremely high temperatures (Dagdag et al., 2015). During the summer months, excessive use of split-unit air-conditioning systems can be attributed to over 80% of the buildings (Suleiman, 2011).

### **Methodology**

The use of questionnaires as a method of collecting data has many advantages – the researcher is able to gain much information from many participants in a short amount of time. It is also cost effective and offers ease of access for both participants and researchers, who can subsequently quantify the results easily. The speed can be further improved by undertaking questionnaires electronically, which means a decreased time frame of waiting for results to be returned.

The questionnaire method was deemed to be most appropriate in order to give a general idea about Libyan domestic residences and the number of occupants and air conditioning use in order to compare between them and the energy consumption. For the questionnaire produced in this study, ten questions in the questionnaire ask about Libyan home types and how many air condition include also how the size of properties and how many people, kitchens, bathrooms, air conditioning units. Moreover, the survey gave indication about locations and the time of start using the air conditioner during the summer days, and time of stop using the air conditioner during the summer days, and month in the year start using air conditioning and finally, month in the year stop using air conditioning.

In spite of these benefits, there can also be several disadvantages. Naturally, people will have different understandings of questions and thus can interpret the meanings in a way which was perhaps not meant by the researcher. This can lead to answers not being given in the scope that was intended (Naoum, 2007).

For this particular questionnaire, a convenient sampling method called the “snowball” method was used, which allowed for quicker responses and wider spread among Libyans in different geographic areas of Libya.

The questionnaire was constructed on 30th of April 2016, and was then distributed electronically. Those contacted to carry out the questionnaire were asked to forward this on to others within Libya. By doing it individually instead of a group distribution meant more responses were received. The survey link was then shared on a social platform, Facebook, to maximise the response rate of students. Then, many individuals shared the link to their group of friends. This further maximised the response rate. The survey was closed on the 26th September 2016. The number of surveys distributed and responses achieved was 724, which gives a result as shown below.

Mohamed et al. (2015) conducted a study across Libya in 2013 through means of a questionnaire, which was written in Arabic and delivered to respondents for self-completion, in order to investigate the main avenues of domestic energy use in Libya. 823 questionnaires were distributed to a random sample from different household types and across different geographical areas with a 52% response rate (i.e. 429 valid questionnaires remained).

The findings regarding the estimated average energy (kW h) used by air-conditioning room in summer and spring are shown in the table below:

Table 1: Estimated average energy (kw/h) and cost (LD) to run appliances for one house (adapted from Mohamed et al., 2015).

Appliance	Rating	No. of appliances	Frequency of use per week	Hours used per day	Total kW h used per year
Air condition room in summer and spring	1000W	3	7	6	6480

## Results and Discussion

### House type

As Figure 2 illustrates below, the finding was that 41% of the participants live in a one storey house. Those who live in a double storey house were 21%. 14% of respondents reported living in a big villa. The rest of the respondents lived in flats: 1% in one bedroom flat, 6% in two bedroom flats, 10% in three bedroom flats, 6% in four bedroom flats and 1% in five bedroom flats.

Houses with one and two storeys make up 61.3% of all housing types, meaning that the majority of Libyan people live in such buildings. This result coincides with results from the MICS survey, which was conducted in 2003. In addition, the number of people living in these houses tend to be five or more, which implies that electricity usage will be excessive. Furthermore, the investigation for building materials for such houses resulted in large energy consumption due to having to meet the needs of the claimant (Akair and Bánhidi, 2007; Suleiman, 2011).

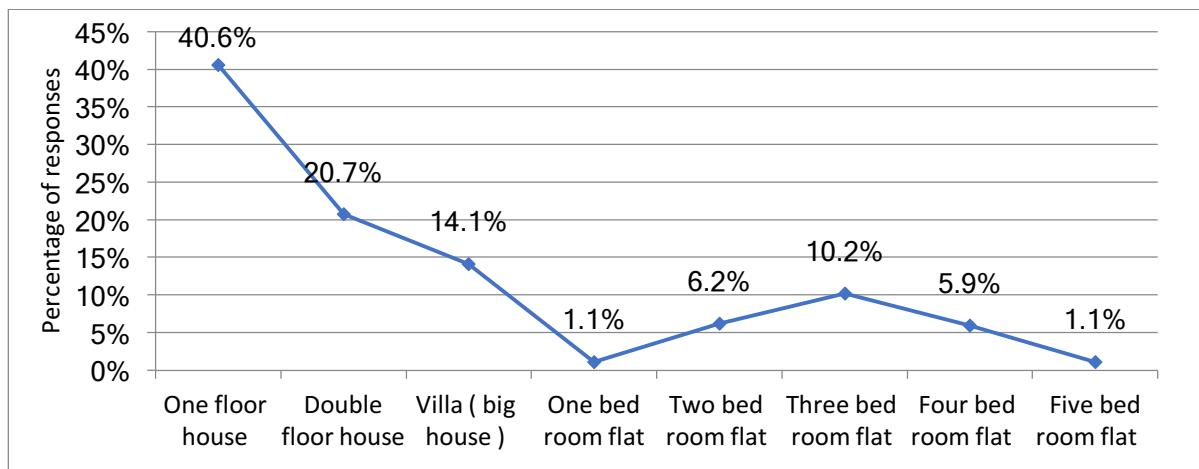


Figure 2.Type of building

### ***Use of air conditioning***

Figure 3 below shows that 78.7% have a number of air conditioning units ranging from 1 to 5, and Figure 4 below shows the peak time of electricity consumption.

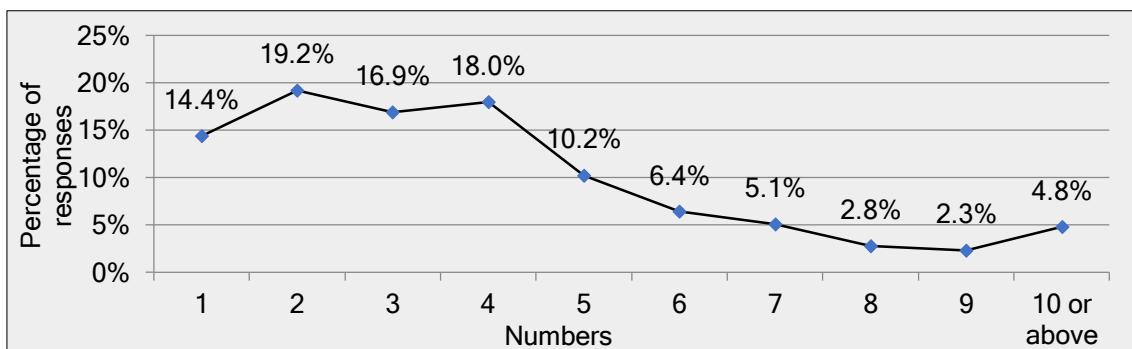


Figure 3. Number of air conditioning units

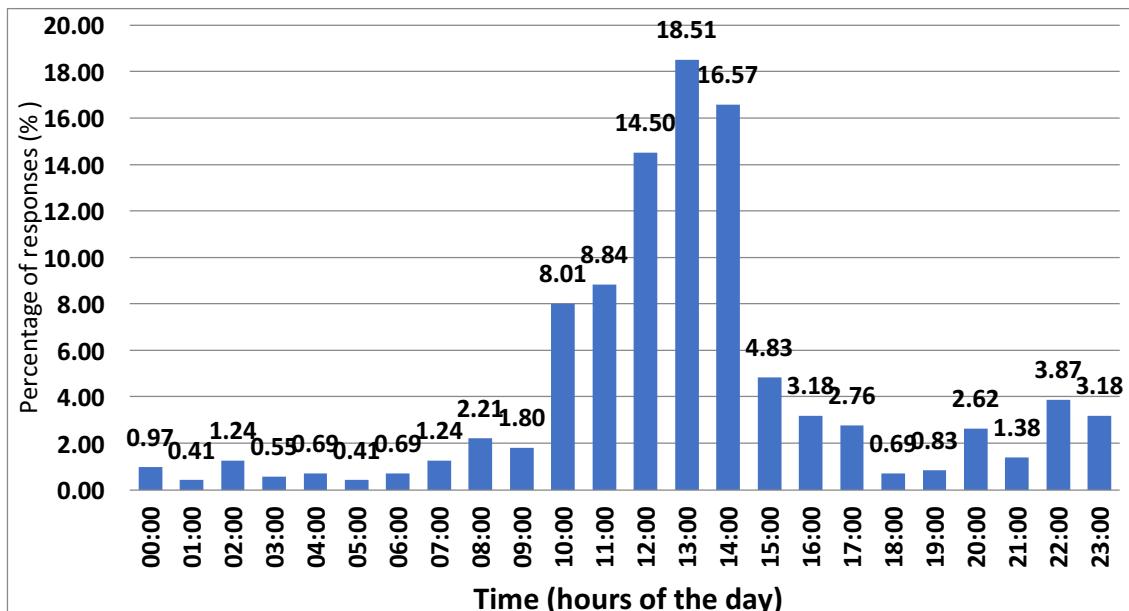


Figure 4. The start of using the air conditioner during the summer days

Therefore, if it is assumed that they have air conditioning units of size 12 BTU/h which will consume about 2.5 kW and estimated energy consumption (EEC) over 6 hours,

The result will be given as the equation below:<sup>2</sup>

$$\text{EEC} = \text{rate power of AC kw/h} * \text{period of operation} * \text{number of AC}$$

$$= 2.5\text{kw} * 6 \text{ hours} * 5 = 75\text{kwh}$$

The time of year that air conditioning was used most frequently was in May with 37% respondents stating this month. Between September and December there were no responses for when air conditioning is turned on, with 1% in January and February. In March 3% began air conditioning, 22% in April, 29% in June and 6% in July as shown in Figure 5. This indicates typical profiles of air conditioning profiles throughout the year.

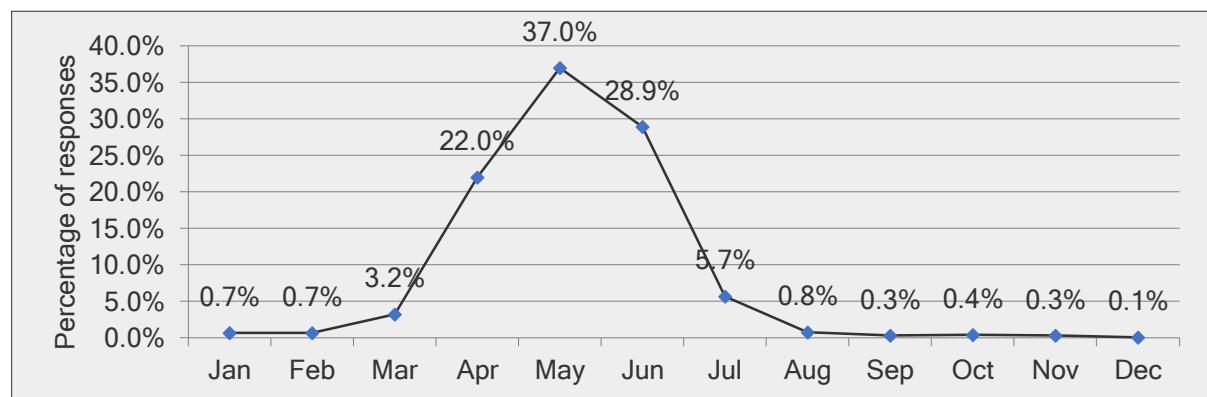


Figure 5. The start of using air conditioning in the month of the year

In Figure 6 below between January and August, respondent numbers were very low. The peak of responses indicated the end of using air conditioning in the month of October, with 45%. 25% responded in September and 17% in November.

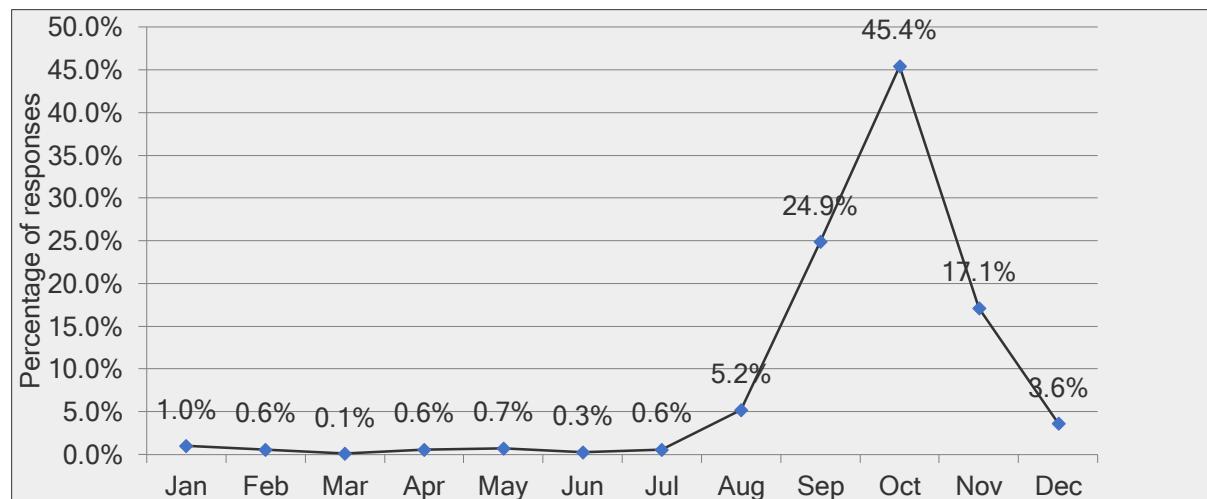


Figure 6. The end of using air conditioning in the month of the year

<sup>2</sup> <https://www.e-education.psu.edu/egee102/node/2106>

## **Conclusion and comments**

If Libyan housing continues to grow at the same rate of development, while GECOL generation rate remains the same, this will inevitably result in a shortage of energy supply that will be unable to meet with increasing demand. This demand, particularly with climate change a factor, is likely to be driven in part by cooling demand. It is therefore vital that we understand current cooling practices and, with that established, design (and retrofit) buildings to perform in a way that can reduce the energy used for this required service.

Future studies should therefore focus on adapting buildings with new technologies but also design features that reduce the need for that technology, employing more effective construction materials, shading and ventilation strategies that will aid in more efficient (and/or less) cooling. The work of this paper will form part of a PhD project by helping to specify a series of archetypal building models, simulated dynamically, to understand the potential of cooling reduction in limiting the growth of peak electricity demand in Libya.

## **References**

- AECOM. (2009). Design criteria for housing projects. The Great Socialist People's Libyan Arab Jamahiriya Housing and Infrastructure Board (HIB) Project Management Department (PMD) Revision Number 00.
- Akair, A. and Bánhidi, L. (2007). Thermal comfort investigation in Libya. *Periodica*
- Alghoul S.K. (2017). A comparative study of energy consumption for residential HVAC systems using EnergyPlus. *American Journal of Mechanical and Industrial Engineering* 2(2), pp.98-103.
- Chernyshev, D (2014). Libya electricity net generation (Billion KWh). Available: <http://libya.opendataforafrica.org/ysbxaw/libya-electricity-net-generation-billion-kwh>. Last accessed 8<sup>th</sup> June 2017.
- Dagdag, M.A.A., Zaika, Y. and Pujiraharjo, A. (2015). Comparisons of house characteristics and facilities in Libya and Indonesia. *IOSR Journal of Mechanical and Civil Engineering*, 12(3),, pp.110-116.
- Deeb, M.J. (2003). Great Socialist People's Libyan Arab Jamahiriya. *The Government and Politics of the Middle East and North Africa*, pp.432-455.
- Kuznik, F., David, D., Johannes, K. and Roux, J.J. (2011). A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews*, 15, pp.379-391.
- Libya, General Electricity Company of Libya (GECOL). (2014). Annual Report, Tripoli.
- Mohamed, A.M., Al-Habaibeh, A., Abdo, H. and Elabar, S. (2015). Towards exporting renewable energy from MENA region to Europe: An investigation into domestic energy use and householders' energy behaviour in Libya. *Applied Energy*, 146, pp.247-262.
- Roaf, S. (2012). Innovative approaches to the natural ventilation of buildings: the imperative for change. *Architectural Science Review*, 55(1), pp.1-3.
- Suleiman, B.M. (2006). Moisture effect on thermal conductivity of some major elements of a typical Libyan house envelope. *Journal of Physics*, 39, pp.547-551.
- Suleiman, B.M. (2011). Estimation of U-value of traditional North African houses. *Applied Thermal Engineering*, 31(11), pp.1923-1928.
- El Bakkush, AFM, Harris, DJ and Bondinuba, FK (2015). The application of building modifications and their effects on energy consumption in buildings. *Journal of energy technologies and policy* 5(8), pp.58-70.
- Ahmad, I., Mokadmy, A and Abughres, SM (1984). Passive heating and cooling strategies for Libya. *Solar and wind technology* 2(1), pp. 1-8.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Uncertainty and sensitivity analysis of residential cooling energy against future climate in hot-humid Taiwan

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**Abstract:** Building cooling energy attributes a relatively large proportion to the total nation-wide energy usage, and the cooling energy is prone to be affected by the future temperature rise and increases the vulnerability of buildings. To formulate adequate strategies counteracting climate change for energy conservation, it is crucial to predict the future cooling energy variation trend. This study aims to quantify the uncertainty of future cooling energy use and to establish the relationship of building envelope parameters to the cooling energy increment. Monte Carlo method was applied to generate residential cases to encompass a variety of building characteristics of condominium. Each case was simulated via EnergyPlus. A global uncertainty and sensitivity analysis method was adopted. The results reveal that although the peak cooling load increases slightly, the annual cooling energy grows dramatically by 25.27%, 54.18% and 109.62% under RCP2.6, RCP4.5, and RCP8.5 respectively in the late 21<sup>st</sup> century since the large increment of the annual A/C operation frequency. The result of sensitivity analysis shows that the top three effective countermeasures to neutralize future cooling energy increment are lowering solar heat gain coefficient of the window, improving insulation of exterior walls, and reducing window-to-wall ratio in hot-humid and cooling dominated region.

**Keywords:** Climate change, hybrid ventilation, building energy consumption, adaptation measure

### Introduction

Energy usage in domestic buildings accounts for more than one-third of the annual total energy consumption in Taiwan, and a large proportion of the energy is mainly used in providing air-conditioning to satisfy the cooling demands (Yang and Hwang, 1993). With the increasing concern of global warming in the past few decades, it has also drawn great attention to the impacts of climate change on the cooling energy, which is highly influenced by the outdoor weather conditions. Wang et al. (2010) analysed the future residential building energy requirements in different regional climates in Australia. They summarized that cities in a cooling dominated region are more sensitive to the changing climate, and the high sensitivity of buildings should be considered during the planning of future energy requirements. As a result, to eliminate the potential threat posing from the changing climate by formulating adequate strategies, it is important to fully understand the possible cooling energy variation under future climatic conditions. In the United Kingdom, Tian and de Wilde (2011) investigated the uncertainties in the projection of the cooling and heating energy of an air-conditioned university building under climate change. In order to devise effective strategies for building energy conservation, Heiselberg et al. (2009) implemented sensitivity

analysis to assess the influence of each design parameter on the energy consumption of an office building in Demark. This research continued to introduce the uncertainty analysis in predicting the trend of residential cooling energy against future climate in hot-humid Taiwan. Three performance indicators are discussed separately to understand the variation of cooling energy in different aspects: (i) peak cooling load, (ii) annual A/C operation frequency, and (iii) annual cooling energy. Moreover, the sensitivity analysis was performed to determine the most effective passive design parameters, which could serve as the practical reference of strategies to counteract climate change.

## **Methodology**

### ***Downscaling method for future weather data***

Computer simulation tools are widely used in building thermal and energy performance analysis, while program EnergyPlus was adopted for hourly dynamic simulation in this study. To explore the future cooling energy variation, future weather data was originated from CanESM2, a global circulation model developed by Canadian Centre for Climate Modelling and Analysis, with three radiative forcing scenarios (RCP2.6, RCP4.8, RCP8.5). Then the future hourly-based typical meteorological years till 2100 were produced through morphing method proposed by Belcher et al. (2005) for cooling energy simulation purpose. Annual mean temperature variation in Taipei, Taiwan under climate change is shown in Figure 1. It is presented that annual mean temperature increases by 0.67°C, 1.7°C and 3.4°C under RCP2.6, RCP4.5, and RCP8.5 scenarios respectively in the late 21<sup>st</sup> century.

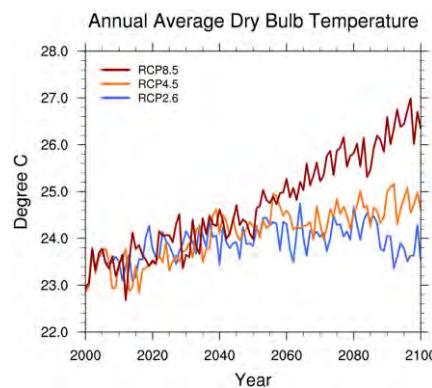


Figure 1. Annual mean temperature variation in Taipei (2000-2100).

### ***Generating simulated cases through Monte Carlo analysis***

The main purpose of this study is to develop appropriate strategies for building energy saving against future climate. Therefore, we should fully understand the trend of cooling energy consumption in advance through uncertainty analysis, aim of which is to discover the likely variation in the output due to the uncertain input. Then sensitivity analysis should be applied to identify the input parameters to which the estimated output of the system is more sensitive (Macdonald, 2002).

Passive design parameters affecting residential energy performance are various and complicated, such as building geometry, windows, and insulation of building envelope materials. The combination of these parameters and other factors, including outdoor climatic conditions, lack of specification of the system and global warming, contributes general uncertainty during the building simulation. Monte Carlo analysis (MCA) based on global

method was applied for sensitivity and uncertainty analysis, since it can be used to quantify the influence of the uncertain input parameters on the response of the output at once (MacDonald, 2009, van Griensven et al., 2006). When applying MCA, 1000 residential cases were generated through random sampling by creating a random number and scaling it to the target variable with its probability density function. In order to simplify the input information about building geometry, six typical apartment floor plans in Taiwan were selected and built when generating 1000 residential cases. The selected floor plans are shown in Figure 2. In which, B stands for bedrooms while L stands for living room. The probability density functions were assumed to be normally distributed for all parameters (except for orientation) represented in Table 1.



Figure 2. Six typical floor plans in Taiwan. B stands for bedroom and L stands for living room.

Table 1. Design parameters with coefficients.

Design parameters	Mean	Standard deviation	Units
Floor area	92.56	13.22	m <sup>2</sup>
Window-to-wall ratio (WWR)	0.35	0.07	-
U-value of window	5.5	0.5	W/m <sup>2</sup> -K
Solar Heat Gain Coefficient (SHGC) of window	0.70	0.05	-
Shading device	0.25	0.20	Shading depth / Window length
Thickness of thermal insulation of external walls	1.27	2.54	cm
Orientation	Eight direction with equal probability.		
Occupancy	4	1	Person
Lighting in living room	10	2.0	W/m <sup>2</sup>
Equipment in living room	9.0	1.8	W/m <sup>2</sup>
Lighting in bedroom	8.0	1.6	W/m <sup>2</sup>
Equipment in bedroom	4	0.8	W/m <sup>2</sup>
Coefficient of performance (COP)	3.3	0.2	W/W

### **Assumption for residential ventilation system and comfort criteria**

Usage of HVAC system energy has the largest contribution to building energy consumption. Therefore, it is essential to define the operating mode of ventilation system, prior to describing the annual cooling energy use of a typical residential HVAC system obtained from dynamic simulation. A split air conditioner is predominant among residential buildings in Taiwan. It operates similarly with mixed-mode ventilation, which is primary running in natural ventilation mode, whenever indoor thermal condition is overheating, air-conditioning is used instead. To assess and determine whether the mechanical cooling was in operation, an adaptive thermal comfort criterion suggested by the ASHRAE Standard 55 was adopted in the study. According to the criterion definition, the optimum indoor thermal comfort operative temperature ( $T_c$ ) is a function of monthly average outdoor temperature ( $T_{om}$ ), and is given in Equation (1). The upper limit of 80% acceptable comfort zone is defined as  $T_c + 3.5^\circ\text{C}$ .

$$T_{oc} = 0.31 \times T_{om} + 17.8 \quad (1)$$

### **Analysis of heating and cooling load under climate change**

On the basis of the simulation result, the variations of annual heating and cooling load between 2000 and 2100 under RCP8.5 with the highest greenhouse gas emissions is shown in Figure 3. It is clear that cooling load varies from 10 between 75 kWh/m<sup>2</sup> in 2000, and its maximum even reaches to 200 kWh/m<sup>2</sup> in 2100. Conversely, the range in heating load reduces. In comparison to the variation trend of cooling load, heating load is almost negligible. As a consequence, the main purpose of the study is to evaluate the effects of building design parameters on the annual cooling load.

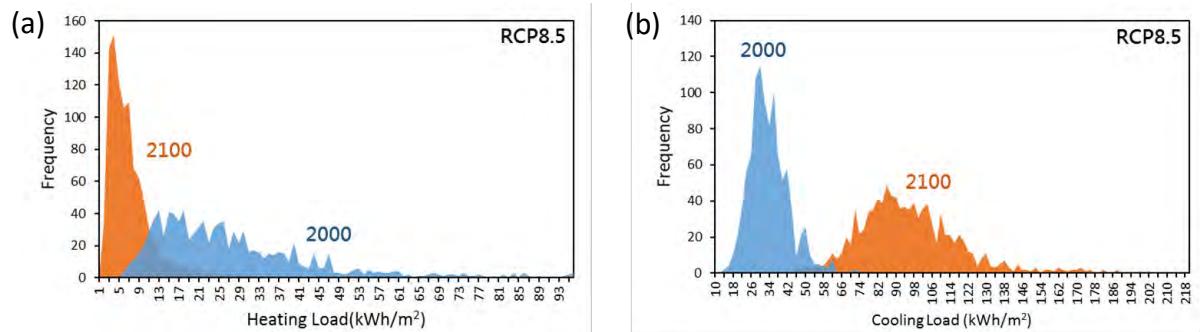


Figure 3. Variation of (a) heating and (b) cooling load between 2000 and 2100 under RCP8.5.

## **Results and discussion**

### **Uncertainty Analysis**

#### **Peak cooling load**

In order to assess the requirement of HVAC system under future climatic conditions, variation of peak cooling load would be the priority to be examined. As presented in Figure 4, the peak cooling load remains almost constant at 80 W/m<sup>2</sup> under RCP2.6, and slightly increases before 2060s under RCP4.5. Nonetheless, overall trend of the peak cooling load rises significantly under RCP8.5 compared to the other scenarios, and ultimately reaches to 92.7 W/m<sup>2</sup> (increases by 18.5%).

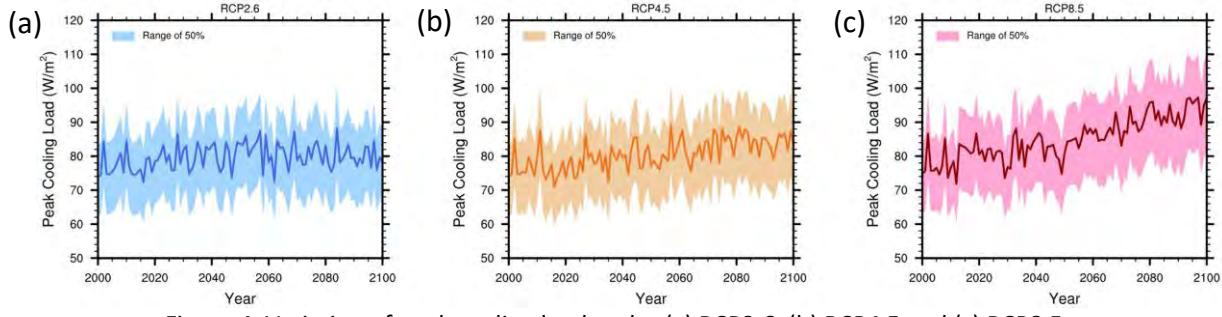


Figure 4. Variation of peak cooling load under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5.

#### *Annual A/C operation frequency*

With a purpose to investigate the usage of air conditioning system in response to global warming, annual A/C operation frequency would be analysed. We introduced “cooling day” as the calculation units to facilitate understanding. Due to different operating schedule for living room and bedrooms, and their corresponding annual A/C operation frequency (cooling day,  $CD$ ) were estimated separately, as shown in Equation (2) - (3).

$$CD_{Liv} = \frac{1}{hr_{Liv}} \sum_{i=1}^{365} t_{Liv,i} \quad (2)$$

$$CD_{Bed} = \frac{1}{n \times hr_{Bed}} \sum_{j=1}^n \sum_{i=1}^{365} t_{Bed,i,j} \quad (3)$$

Where  $t_{Liv}$  and  $t_{Bed}$  are the annual A/C operation frequency in hours,  $hr_{Liv}$  and  $hr_{Bed}$  are the occupancy schedule from EnergyPlus which equal to 16 hr/day and 13 hr/day respectively, and  $n$  is the number of the bedrooms in each case.

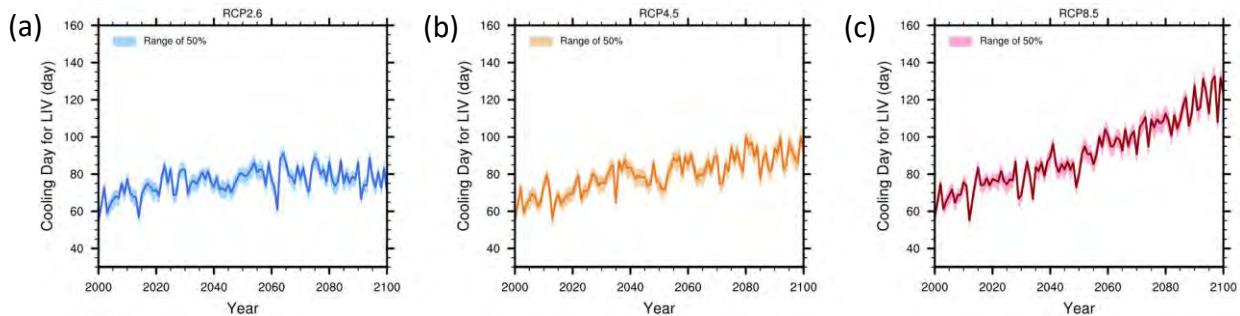


Figure 5. Variation of annual cooling day for living room under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5.

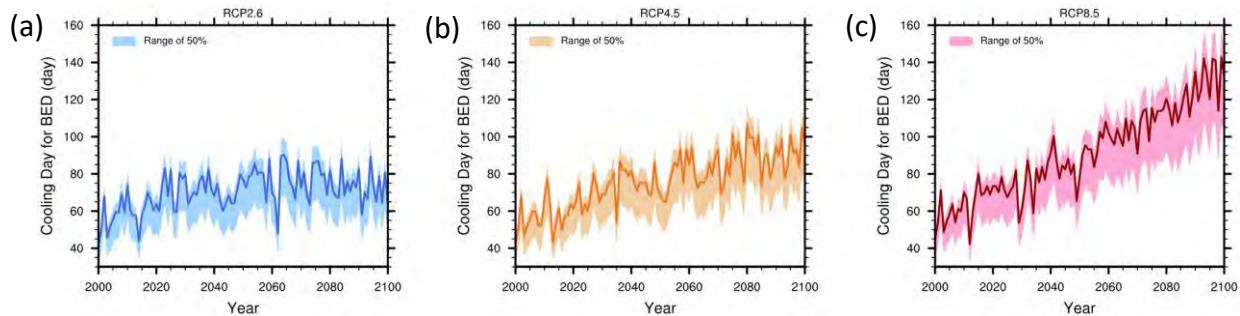


Figure 6. Variation of annual cooling day for bedrooms under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5.

Figure 5 shows the annual A/C operation frequency for living room, while Figure 6 shows the part for bedrooms. The annual cooling days for both living room and bedrooms increase before 2060s and drops eventually under RCP2.6, and as for RCP4.5, it rises just before remaining steady since 2070s. Obviously, a dramatic increment appears under the most extreme scenario, RCP8.5, and it increases to 115-120 days in the late 21<sup>st</sup> century (more than 68.7% and 104.5% compared to the present for living room and bedrooms respectively). It is speculated that the annual A/C operation frequency has a much higher growth rate than the peak cooling load under the future meteorological conditions.

#### *Annual cooling energy*

The general trend of the peak cooling load and the annual A/C operation frequency are learnt from the above analysis result. Then we start focusing on the potential impact on building enegy performance in terms of annual cooling energy. As shown in Figure 7, the long-term trend of the annual cooling energy follows to that of the annual A/C operation frequency. The figure illustrates that the cooling energy consumption is under control at 15.37 kWh/m<sup>2</sup> in the late 21<sup>st</sup> century under RCP2.6; in contrast to the former scenario, cooling energy consumption grows significantly to 26.74 kWh/m<sup>2</sup> under RCP8.5, which is almost twice as the amount of the present.

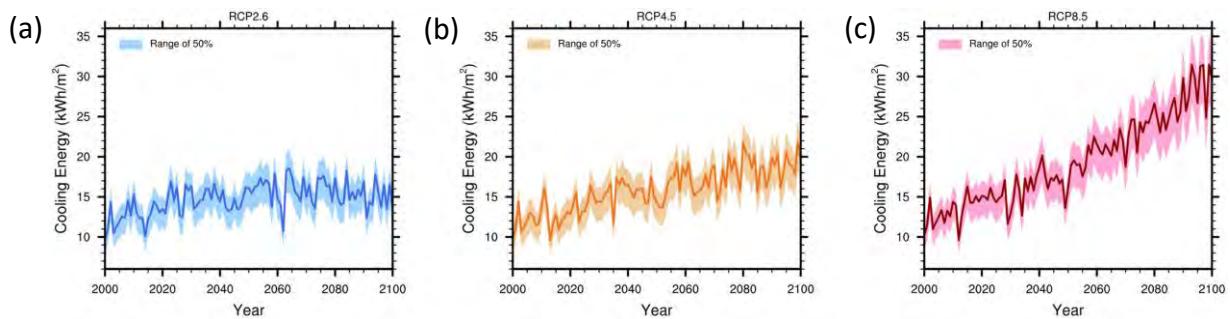


Figure 7. Variation of annual cooling energy under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5.

As displayed in Table 2, the increase of the peak cooling load is inconsiderable and does not exceed more than 20% among all the scenarios. Although there are both upward trends in the amount of the annual cooling day for living room and bedrooms, increment of the latter is more noticeable since most of the bedrooms are adjacent to external walls, and thus, the changing in outdoor climate could directly affect the increment. It could be summarised that at the end of the century, despite the slightly increment in peak cooling load, the annual cooling energy ultimately increases by 25.27%, 54.18% and 109.62% under RCP2.6, RCP4.5, and RCP8.5 scenarios respectively as the annual A/C operation frequency increases.

Table 2. Summary of the three indicators in different time slices under three scenarios.

Scenario	Peak Cooling Load (W/m <sup>2</sup> )			Annual Cooling Day (Day)				Annual Cooling Energy (kWh/m <sup>2</sup> )				
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Current (2000-2015)	76.97	77.16	78.24	66.74	66.33	68.43	56.94	56.63	59.86	12.27	12.21	12.76
Near Future (2016-2040)	79.48	77.92	81.38	75.93	75.67	78.22	70.54	69.42	73.85	14.68	14.47	15.34
Far Future (2076-2100)	80.16	84.41	92.69	78.40	90.17	115.42	73.90	90.91	122.42	15.37	18.82	26.74
Increment	4.15%	9.39%	18.47%	17.4%	35.9%	68.6%	29.7%	60.5%	104%	<b>25.2%</b>	<b>54.2%</b>	<b>109%</b>

## Sensitivity Analysis

A regression analysis of the annual cooling energy use on outdoor air temperature under climate change was performed. As presented in Figure 8, it reveals that the annual cooling energy consumption would increase by 5.01 kWh/m<sup>2</sup> per household as the outdoor air temperature increases by 1°C relative to 2000, under the hypothesis that all the design parameters remain unchanged during the whole 21<sup>st</sup> century. Therefore, it is crucial to develop counteracting strategies with the aim of maintaining the annual cooling energy usage at current levels.

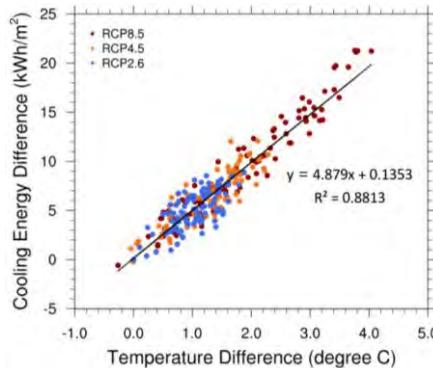


Figure 8. Regression of annual cooling energy use on temperature difference from 2000.

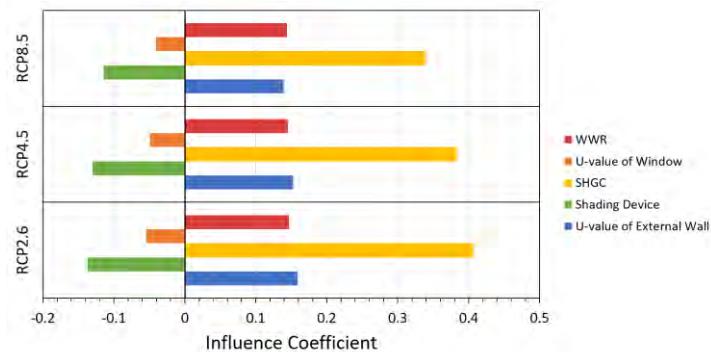


Figure 9. Result of influence coefficient for each design parameter under different scenarios.

To assess the influential passive design parameters which could be regulated and determine their levels of impact on cooling energy consumption, the sensitivity analysis was applied in the study. We selected and averaged the bottom 10% ( $IP_{0\sim10\%}$ ) and the top 10% ( $IP_{90\sim100\%}$ ) of each design parameter, as well as their corresponding annual cooling energy ( $OP_{0\sim10\%}$  and  $OP_{90\sim100\%}$ ), and then calculated the influence coefficient (IC) using the following equation based on the study from Lam and Hui (1996).

$$IC = \frac{\Delta OP \div \left( \frac{OP_{0\sim10\%} + OP_{90\sim100\%}}{2} \right)}{\Delta IP \div \left( \frac{IP_{0\sim10\%} + IP_{90\sim100\%}}{2} \right)} \quad (4)$$

If a parameter causes a change in cooling energy and the sensitivity of  $IP$  with respect to  $OP$  could be estimated in terms of the influence coefficient. The IC of each design parameter is shown in Figure 9. IC for each design parameter tends to decline under RCP8.5 since the outdoor climatic conditions with higher air temperature have a greater impact on cooling

energy use. Nonetheless, the range of variation for WWR is not wide enough (the largest value of WWR is 0.55), so the study could not reflect the insulation of the window properly in the result. Thus, it should be more accurately when selecting probability density function and coefficients for each design parameters.

It is apparent that the absolute values of IC for solar heat gain coefficient of the window, U-value of the exterior walls and window-to-wall ratio are the top three maximums. This means that introduction of improving insulation of exterior walls, and reducing window-to-wall ratio should be the major concern for architects and engineers during the design process of residential buildings, which consume relative low cooling energy. Moreover, low solar heat gain coefficient of the window is more important than low U-value of that during the selection of the glazing, since the influence of the former on the cooling energy reduction is much more than the influence of the latter. These countermeasures would contribute lower building energy consumption and increase the resilience of residential buildings in facing global warming.

## Conclusion

1. In Taiwan, since the demand on heating load of a residential building is negligible, cooling load becomes the dominant energy requirements and should be consider as the major problem to deal with when formulating adequate strategies.
2. Although the peak cooling load increases slightly, the annual cooling energy ultimately increases dramatically by 25.27%, 54.18% and 109.62% under RCP2.6, RCP4.5, and RCP8.5 respectively in the late 21st century owing to the large increment of annual A/C operation frequency.
3. If all design parameters remain unchanged, the annual cooling energy would increase by 5.01 kWh/m<sup>2</sup> per household as the outdoor air temperature increases by 1°C relative to 2000. Thus, passive design strategies must be adopted to save building energy usage.
4. Lowering solar heat gain coefficient of the window, improving insulation of exterior walls, and reducing window-to-wall ratio are the first three appropriate preferences of strategy.

## References

- Belcher, S. E., Hacker, J. N. & Powell, D. S. (2005). Constructing design weather data for future climates. *Building Services Engineering Research And Technology*, 26, 49-62.
- Heiselberg, P., Brohus, H., Hesselholt, A., Rasmussen, H., Seinre, E. & Thomas, S. (2009). Application of sensitivity analysis in design of sustainable buildings. *Renewable Energy*, 34, 2030-2036.
- Lam, J. C. & Hui, S. C. M. (1996). Sensitivity analysis of energy performance of office buildings. *Building and Environment*, 31, 27.
- Macdonald, I. A. (2002). *Quantifying the effects of uncertainty in building simulation*. PhD thesis, University of Strathclyde.
- MacDonald, I. A. (2009). Comparison of sampling techniques on the performance of Monte Carlo based sensitivity analysis. *Building Simulation 2009 Conference Proceedings*, 992-999.
- Tian, W. & de Wilde, P. (2011). Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: A UK case study. *Automation in Construction*, 20, 1096-1109.
- van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, A. & Srinivasan, R. (2006). A global sensitivity analysis tool for the parameters of multi-variable catchment models. *Journal of Hydrology*, 324, 10-23.
- Wang, X. M., Chen, D. & Ren, Z. G. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment*, 45, 1663-1682.
- Yang, K. H. & Hwang, R. L. (1993). The analysis of design strategies on building energy conservation in Taiwan. *Building and Environment*, 28, 429-438.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Energy and thermal performance assessment of existing residential buildings: the first step to introducing successful retrofitting strategies in Albania

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**Abstract:** This paper presents the findings of a study conducted in Albanian residential buildings. It aims to get insights of energy and thermal performance of the existing housing stock, as well as the effect that human behaviour has on the indoor environment. The methodology adopted comprised building surveys, occupant survey and continuous monitoring of outdoor and indoor environmental conditions during the summer and winter to cover for seasonal variations. 49 case studies were randomly selected to represent various Albanian housing typologies defined for this study. It is found that energy consumption was up to 97% over the baseline, and more than two third was consumed for heating the space in winter. The findings also indicate a disparity between the preferred thermal conditions and those experienced, especially in winter where residents found it very difficult to prevent the very high fluctuation of temperatures. Other occupants' behaviours associated with individual perceptions and cultural bearings are highlighted. Therefore, using these findings to inform and calibrate the baseline energy modelling will provide better estimations on energy savings for future retrofitting programmes.

**Keywords:** Energy performance, comfort, human behaviour, pre-retrofit survey, monitoring

### Introduction

Notwithstanding that energy retrofitting of existing housing stock offer a great potential in energy savings, several energy retrofitting programs have shown that they are lower than anticipated (Gupta and Gregg, 2012; Sunikka-Blank and Galvin, 2012), partly because of considerable assumptions and predictions used for energy modelling, due to a lack of data about various aspects of the building (Zero Carbon Hub, 2014). Furthermore, regional, social and cultural variation including differences in climatic conditions, income level, building materials and techniques, building stocks are complex and the boundaries are difficult to define and probably they have been underestimated (Kohler, 1999). Therefore, the model calibration with the real data on energy and environmental performance gathered through pre-retrofit monitoring of the building (Gupta and Gregg, 2016), including the possibility of integrating the occupants' behaviours into building simulations based on measured observations rather than assumptions (Guerra-Santin et al, 2016), is vital in minimising the performance gap between the expectations and outcomes.

Within this context, this paper investigates the energy and thermal performance of various archetypes in Albania through continuous monitoring of indoor and outdoor environmental conditions, building surveys and occupant survey, and examines the occupant's behavioural effect in achieving thermal comfort.

## Methodology

This research is part of an ongoing PhD study that aims to investigate the most effective retrofitting strategies for energy savings and improving thermal comfort in residential buildings in Albania. A socio-technical approach was used to collect quantitative and qualitative data from 49 households representing eight various archetypes of residential buildings in Albania, consisting of:

*Building surveys* to gather information regarding archetypes and energy use. Electricity bills were also obtained for 36 out of 49 dwellings.

*Questionnaire-guided interviews* to get insights of how and when the house is used, occupants' attitudes and habits, and other everyday practices in their home, as well as to assess their comfort sensation and preference in summer and winter.

*Continuous monitoring of the outdoor and indoor temperature in the living room and main bedroom of 49 dwellings in summer and winter*, to assess the thermal comfort in the house.

Based on dwellings statistics, the sample chosen for monitoring is closely representative of Albanian housing apart from semi-detached houses, which are under-represented.

Table 1. Statistics of residential buildings in Albania

Type	Albanian residential buildings		Dwellings		Sample	
	Frequency	%	Frequency	%	Frequency	%
Detached	88,804	80.5	88,804	33.9	17	34.6
Semi-detached	10,184	9.2	25,666	9.8	1	2
Terraced	4,351	3.9	14,142	5.4	2	4.1
Flat	6,944	6.3	133,291	50.9	29	59.3
Total	110,283		261,903		49	

Table 2. Frequency of key characteristics in the sample

Category	Description	Frequency	%
Year of construction	Pre-1960	4	8.2
	1961-1990	12	24.5
	After 1991	33	67.3
Construction type	Solid brick / stone external walls	8	16.3
	Concrete blocks	3	6.1
	Pre-fabricated	3	6.1
	Silicate brick	5	10.2
	Hollow brick	24	49
	Insulated walls	6	12.2
Ventilation / cooling scheme	Natural ventilation	3	6.1
	Mixed ventilation (natural + air conditioning)	46	93.9

## Energy consumption

Energy consumption data is used to get insight of air-conditioning usage during summer and winter. In almost all dwellings, electricity consumption increases during the winter months (November-March) with its peak in January and in summer in July, associated with heating and cooling respectively.

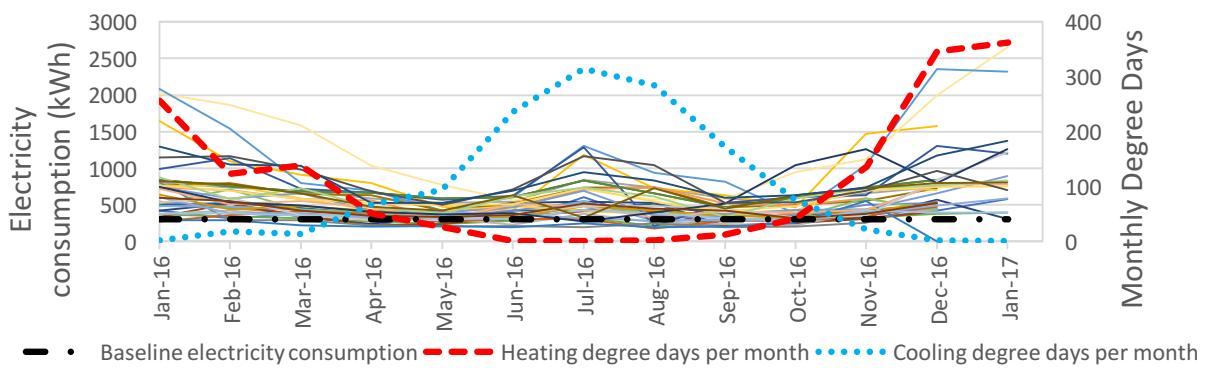


Figure 1. Electricity consumption from January 2016 to January 2017

Source of degree days: ([www.degreedays.net](http://www.degreedays.net), 2017)

43% of the dwellings are heated for half of the year and two of them are heated for as long as eight months of the year and most of the dwellings are cooled for three (20%) and four (45%) months of the year. Based on the baseline electricity consumption of 300kWh (ERE, 2009), needed in one household that does not perform heating or cooling with electricity, an estimation of electricity consumption used for heating and cooling of each dwelling in the sample.

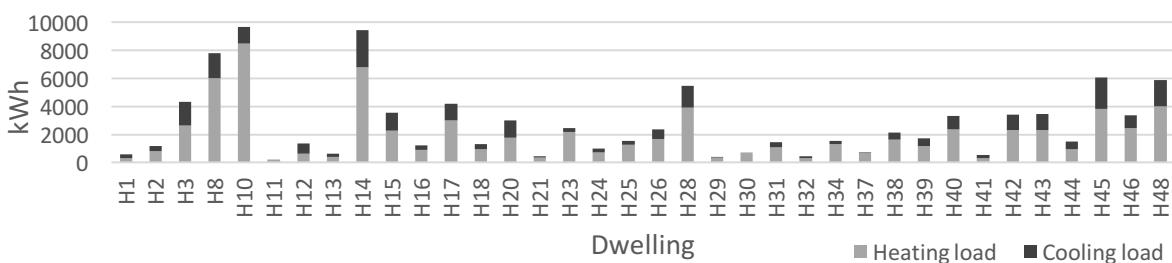


Figure 2. Estimated heating and cooling loads (kWh) based on electricity bills

Notwithstanding that energy data available include only electricity consumption, it can be noticed that most of energy consumed over the base load is for heating rather than cooling the homes. Furthermore, 65% of households also consider heating of their homes more important than cooling.

### Temperature variations and thermal comfort in summer

The indoor temperature of 49 living rooms and 42 main bedrooms were monitored from 30 June to 12 August 2016 at half-hourly intervals, to cover the hottest season of the year in the Albanian climate. The outdoor temperature ranged between 19.6°C to 41.1°C, while the indoor temperature ranged from 19.5°C to 36.5°C in living rooms and 19.5°C to 37°C in bedrooms. The indoor temperatures were well above the recommended figures from the guidelines (23°C -25°C) (CIBSE, 2006). Even more, half of the dwellings had indoor temperatures constantly over 25°C. The dwellings that experience the highest temperatures, had the largest temperature variation.

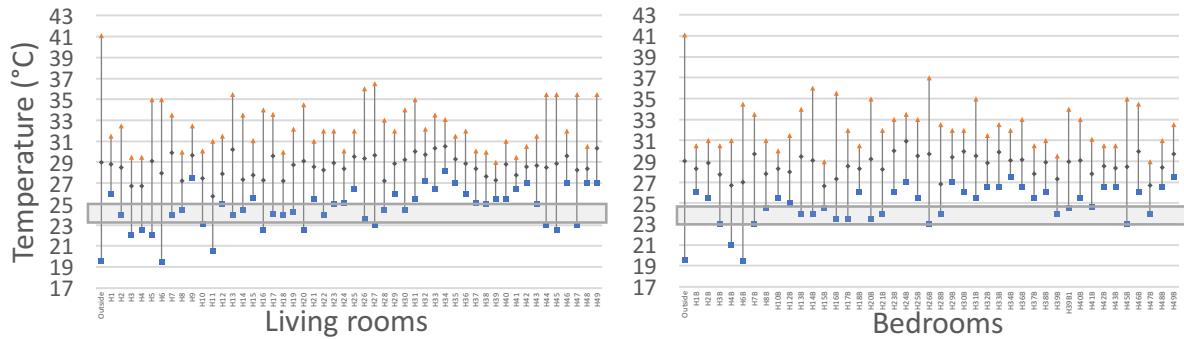


Figure 3. Minimum, maximum and mean temperatures for each dwelling during the summer

Subjective evaluation of the thermal environment was provided using a 7-point ASHREA scale for the thermal sensation evaluation and a 5-point scale for thermal preference. 86% of the households reported to feel warmer than neutral during the summer, from which more than 40% of them were feeling hot. Only 6% of the households required no change and approximately 60% wanted to feel much cooler.

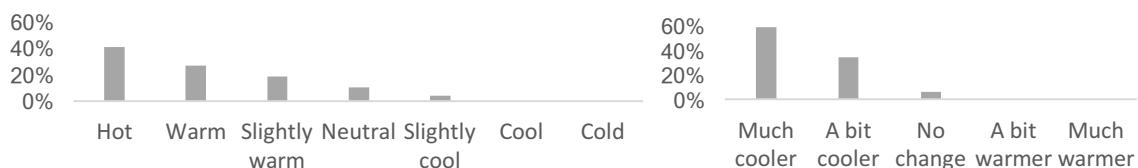


Figure 4. Percentage distribution of thermal sensation votes (left) and thermal preference votes(right)

The standardized indoor mean temperatures for each thermal sensation vote were calculated (Table 3), and it was found that occupants were feeling hot in an indoor mean temperature of 29°C (with a standard deviation of 1.1) and a maximum and minimum mean temperature of 30.5°C and 27.3°C respectively. The temperature range for the dwellings in which the households reported to be feeling warm or slightly warm were very similar. Interestingly, the occupants felt neutral for temperature close to the dwellings in which the resident were feeling hot. There were only two dwellings in which the occupants were feeling slightly cool, and indeed the mean, maximum and minimum temperatures were lower than in the other cases.

Table 3. Mean indoor temperatures of dwellings for each value of thermal sensation vote reported

#### How do you feel during the summer?

Slightly warm		Neutral		Slightly cool		Cool		Cold	
<b>Mean temperatures in living rooms</b>									
Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
29.0	30.5	27.3	28.4	29.7	27.2	28.4	29.9	26.7	28.7
<b>Standard Deviation</b>									
1.1		0.8		1.2		0.5		1.0	

#### Temperature variations and thermal comfort in winter

The indoor temperature of 45 living rooms and 42 main bedrooms was monitored from 5 January to 16 February 2017 at half-hourly intervals, to cover the cold season. The outdoor temperature ranged between -5.5°C to 18.5°C, while the indoor temperature ranged from -

6°C to 29.5°C in living rooms and -5.5°C to 29.5°C in bedrooms. For most of the dwellings, the indoor temperature was below the recommended temperatures from the guidelines (22°C - 23°C) for living rooms and (17°C -19°C) for bedrooms (CIBSE, 2006). 19 out of 45 dwellings monitored did not reach temperatures 22°C or above. Some of the dwellings have registered temperatures close to the outdoor temperature, meaning that they have little or no heating at all and windows could possibly have been left open during the day. A very high temperature variation can be noticed in living rooms varying from 6.5 degrees (H39) to 33 degrees (H25), indicating a big problem in keeping the adequate thermal comfort in Albanian homes in winter. Moreover, the dwelling that had the largest indoor temperature variation, had recorded temperatures as low as 0°C to -6, which is the same as the outside temperature.

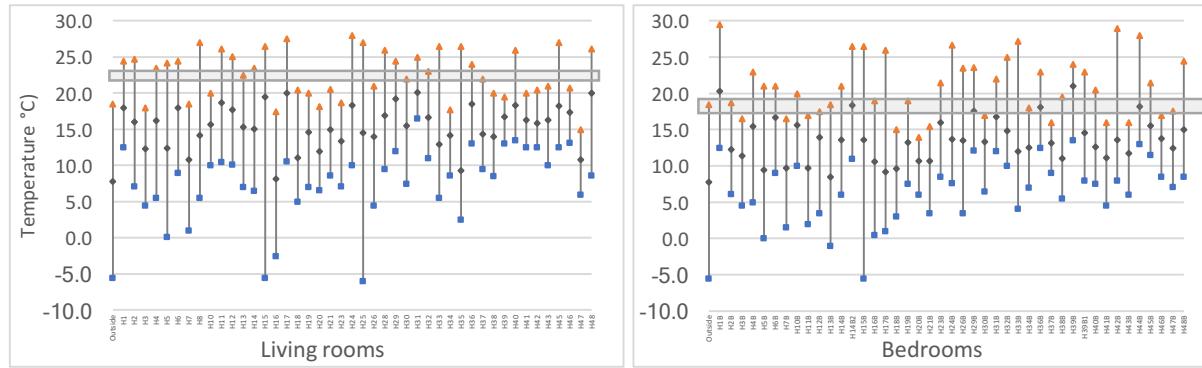


Figure 5. Minimum, maximum and mean temperatures for each dwelling during the winter

A considerable but low correlation ( $r=0.33$ ) is found between the mean temperature and the main construction material. More importantly, the dwellings that had applied wall insulation had higher indoor mean temperatures, which highlights the need of fabric improvement for improvement thermal comfort in Albanian homes.

75% of the households reported to feel colder than neutral during the winter, from which 39% were feeling cold. Nearly half of them (49%) preferred to feel much warmer and 37% preferred a bit warmer. Only 12% of the participants were feeling neutral during the winter and 4% preferred no change of temperatures.

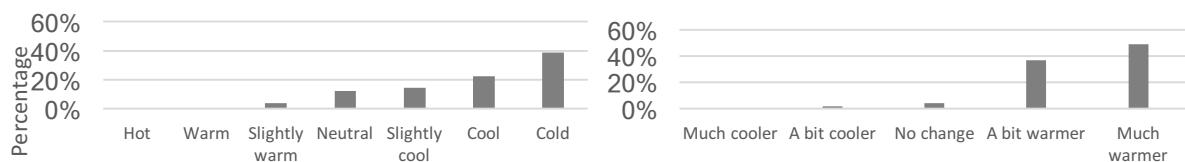


Figure 6. Percentage distribution of thermal sensation votes (left) and thermal preference votes(right)

Most of the occupants that were feeling cool or cold during the winter wanted the environment to be much warmer. Comparing the indoor mean temperatures for each thermal sensation vote (Table 4), it is found that occupants were feeling cold in an indoor mean temperature of 15.1°C (with a standard deviation of 3.1) and a maximum and minimum temperature of 20.1°C and 8.2°C respectively. However, there is not a large variation of indoor mean temperatures for which the occupants were feeling neutral, slightly cool or cool. The determinant factor for the thermal sensation votes distribution might be the value of the minimum mean temperature, which is higher for the dwellings in which the occupants were feeling slightly warm and neutral with values of 16.9°C and 10.8°C respectively.

Table 4. Mean indoor temperatures of dwellings for each value of thermal sensation vote reported  
**How do you feel during the winter?**

Slightly warm			Neutral			Slightly cool			Cool			Cold		
<b>Mean temperatures in living rooms</b>														
Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
17.8	18.7	16.9	16	19.2	10.8	15.2	20.1	9.3	16	19.5	14	15.1	20.1	8.2
<b>Standard Deviation</b>														
	1.3			3.3			4.1			2.0			3.1	

### Human behaviour effect

Focus should be in different practices and behaviours related to comfort to understand the energy consumption of households (Gram-Hanssen, 2010). Air conditioning was the most popular cooling type in the sample and still, maximum mean temperatures exceeded the value of 30 degrees. This was mainly because localised cooling or heating were performed in all cases, most of the time using convective cooling and heating, which produced relatively lower temperatures in living rooms than bedrooms in summer and vice versa in winter. Residents tended to open windows in the morning, evening and night, due to the cool outdoor air. However, the dwellings with higher variation of temperature, had on average four months of cooling and dwellings with shorter cooling period had an indoor mean temperature variation between five degrees to eleven degrees. The indoor mean temperatures during the winter are relatively lower in bedrooms than in living rooms because bedrooms were mainly unheated. In some of the dwellings, internal doors of the bedrooms that had direct access in living rooms were kept open to circulate the air. However most of the time it was a localised heating.

*"We can't afford to keep the electric oil filled radiator on all the time. So, we switch it on only when it is very cold and we cover it with a blanket, so we heat up quickly"*

Most of the households turned the heating off as soon as the occupants achieved a temporary thermal comfort, to save energy. One resident said:

*"We simply cannot afford to keep the air conditioning on all the time"*

Most of the dwellings start to be heated in November and the heating is greatly on until March or April. Most of the dwellings are heated in morning and evening which is the time when they are fully occupied and there are no indecent solar gains. Only seven dwellings were heated during the nights and there are noticed higher main temperature in bedrooms of these dwellings compared with the ones that are not heated during the night. Most of the households opened the windows in the morning just for fresh air exchange. In contrast, in most of the dwellings that were heated all day, the indoor temperature was controlled by opening and closing the windows. There is a low correlation factor ( $r=0.255$ ) between the type of heating and type of control. However, it is interesting to investigate whether certain control options are related to the types of heating. Indeed, using the convective cooling and heating systems can give the commodity to easily turn it on/off or change the temperature settings, while the heat produced from the wood stoves is more difficult to be controlled, making the resident opening the windows when it is too hot.

There are other considerations related to cultural norms for some of the families, especially those who live in detached houses (where the security issues are not a concern), to leave the door open for visitors and showing them their hospitality. Thermal preferences were also very different within some of the households. One female participant said:

*"I want fresh air all the time and keep the windows open all day in summer and mostly in winter. I don't care what my husband thinks or feels. He can get a blanket"*

Table 5: Standardized indoor temperature in living rooms by behavioral practices in summer and winter

Summer						Winter					
	n	Mean	Max	Min	SD		n	Mean	Max	Min	SD
<b>Main type of cooling / heating</b>											
No cooling	2	27.2	28.6	25.8	2.0	Convective heating	31	15.4	20.1	10.1	3.4
Air conditioning	51	28.4	30.1	27.0	0.9	Wood stove	10	15.6	20.1	8.2	5.3
Electric cooler	7	29.5	30.5	28.2	0.9	LPG heater	4	16.3	18.0	14.2	1.9
<b>How do you control the room temperature?</b>											
No control	2	27.2	28.6	25.8	2.0	Open doors / windows	13	14.5	20.1	8.2	3.9
Open doors / windows	16	29.0	30.5	27.3	0.9	Turn the heating on / off	27	15.4	20.1	9.3	2.8
Turn the cooling on / off	26	28.5	30.3	26.7	1.1	Turn the heating up/down	5	14.0	14.0	14.0	.
Turn the cooling up/down	5	28.4	30.1	27.2	1.2						
<b>When do you switch the cooling / heating on during the day?</b>											
No cooling	3	28.5	30.5	25.8	2.4	Morning	1	16.6	16.6	16.6	.
Mid-day	1	28.8	28.8	28.8	.	Mid-day	1	18.0	18.0	18.0	.
Afternoon	17	28.6	30.3	26.7	1.1	Afternoon	5	15.0	19.2	9.3	4.1
Evening	3	28.4	29.3	27.2	1.1	Evening	6	15.7	18.4	14.2	1.6
Afternoon and evening	20	28.8	30.3	27.2	0.8	Morning and evening	16	15.8	20.1	8.2	3.3
All day	5	27.9	30.1	27.2	1.3	All day	6	16.8	20.1	12.4	3.0
						Afternoon and evening	10	14.5	18.7	10.8	2.7
<b>Do you cool / heat the house during the night?</b>											
No	36	28.8	30.5	26.7	1.0	No	38	15.7	20.1	8.2	2.9
Yes	13	28.1	30.3	25.8	1.3	Yes	7	15.2	20.1	9.3	3.7
<b>When do you open the windows in summer / winter?</b>											
Afternoon	2	28.8	28.9	28.7	0.1	Morning	41	15.6	20.1	8.2	3.1
Evening	2	29.5	30.3	28.7	1.1	Afternoon	1	14.7	14.7	14.7	.
During the night	2	26.5	27.2	25.8	1.0	All day	1	15.0	15.0	15.0	.
Morning and evening	21	28.5	29.9	26.7	1.0	When it is too hot	2	16.7	18.3	15.1	2.3
All day	8	29.1	30.2	28.2	0.8						
All day and night	5	29.2	30.5	27.3	1.3						
When the cooling is off	1	29.1	29.1	29.1	.						
Evening and night	8	28.2	29.7	27.2	0.9						

## Discussion

It is revealed from this research that there were particularly bad thermal conditions in winter with very low temperatures and high fluctuation during the day up to 33 degrees. Convective cooling and heating was mainly used and it was used for longer period in winter than in summer, suggesting that heating was more crucial than cooling in Albanian houses.

Furthermore, cooling and heating were performed locally in all dwellings and for short periods of time during the day in most of them.

No significant correlation was found between indoor temperatures and building characteristics such as typology, year of construction and number of stories, apart from a weak correlation between indoor mean temperatures and the main construction material.

In summer, statistically similar temperatures were both reported as neutral and hot (around 29°C). However, only 10% was feeling neutral at this temperature, meaning that it could be related to individuals and their preferences. In addition, residents were feeling slightly cool for mean temperatures of 26.5°C. In winter, the occupants were feeling cold for temperatures 15°C and neutral for mean temperatures of 16°C. Economic factor was determinant for not being able to keep the house comfortable in summer and winter. However, cultural issues were associated with some behavioural practices which might be determined in achieving successful outcomes for future retrofitting projects.

## Conclusion

The analysis carried out for this research provides evidence of the energy and thermal performance of residential buildings in Albania, as well as occupants' thermal perceptions and preferences. It was found that heating the Albanian dwellings is more crucial than cooling and a way to achieve energy savings is to aim to decrease the duration in months, especially for heating. Furthermore, special attentions to be considered for unintended consequences such as overheating, which could increase the energy consumption for cooling. Given these findings, it is essential to use them to inform and calibrate the baseline energy models, prior to investigating any retrofitting strategies, to minimise the performance gap created by assumptions and predictions.

## References

- CIBSE (2006). *Environmental design: CIBSE Guide A*. Norwich: CIBSE
- ERE (2009). Konsumi i energjise elektrike ne familje. Tirana: ERE.
- Gram-Hanssen, K. (2010). Residential heat comfort practices: understanding users'. *Building Research & Information*, 38(2), pp. 175-186.
- Guerra-Santin, O., Herrera, N.R., Cuerda, E. and Keyson, D. (2016). Mixed methods approach to determine occupants' behaviour – Analysis of two case studies. *Energy and Buildings*, 130, pp. 546-566
- Gupta, R. and Gregg, M. (2012). Appraisal of UK funding frameworks for energy research in housing. *Building Research & Information*, 40(4), pp. 446-460.
- Gupta, R. and Gregg, M. (2016). Do deep low carbon domestic retrofits actually work? *Energy and Buildings*, 129, pp. 330-343.
- Kohler, N. (1999). The relevance of Green Building Challenge: an observer's perspective. *Building Research & Information*, 27(4-5), pp. 309-320.
- Sunikka-Blank, M. and Galvin, R. (2012). Introducing the pre-bound effect: the gap between performance and actual energy consumption. *Building Research & Information*, 40(3), pp. 260-275.
- [www.degreedays.net](http://www.degreedays.net/) (2017). Degreedays.net – Custom Degree Days Day data. Available at: <http://www.degreedays.net/> (Accessed:25.02.2017)
- Zero Carbon Hub (2014). Closing the gap between design and as-built performance. Evidence review report. London: Zero Carbon Hub.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Impact of building envelope construction on thermal comfort: a parametric analysis of modern, low income housing in south-west Nigeria for current and future climates**

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**Abstract:** Studies have shown that the biggest climate impacts will take place in the tropical countries of Africa. This paper examines how different building construction choices influence the thermal performance of contemporary low-income housing in the south-west Nigeria region for present and future climates. Climate-resilient and responsive dwellings need to be developed that can adapt to changing tropical climates whilst being socio-economically suited to their geographical context. This study examines the evidence of climate change in south-west Nigeria and how the region's contemporary low-income housing currently performs from energy and thermal comfort perspectives. Then, the study uses dynamic thermal modelling and current and future climate data sets to test, parametrically, how changes to the dwelling's envelope can be made to reduce climate change impact and improve occupant thermal wellbeing. As such, the typical south-west Nigerian family house type was modelled and parametrically optimised. The findings showed that some modifications to the walls, roofs and floors can help improve thermal comfort in present and future south-west Nigerian climates. The study concludes that improvements to thermal comfort and climate change resilience are realistically achievable by small modifications to a dwelling's envelope.

**Keywords:** Vernacular housing, climate-resilience, building envelope performance, parametric optimisation

### **Introduction**

Climate change is a phenomenon associated with industrialisation, urbanisation and the accompanying increase in greenhouse gas (GHG) emissions from the burning of fossil fuels (Thiele, 2013; Johnson et al, 2015). Despite these factors being associated primarily with the developed world, the Intergovernmental Panel on Climate Change (IPCC) identified the continent of Africa as being at risk from the impacts of climate change, with the threat of higher land temperatures, changes in precipitation and stresses on water availability (Niang et al, 2014). Nigeria will experience most of these predicted impacts and so strategies must be developed that make Nigeria more resilient to climate change. Ijeoma (2012) identified resilient housing as a key component of this strategy. Climate responsive architecture addresses climate change by trying to use passive measures to work with the prevailing climate and to reduce the need for fossil fuel energy. Climate-responsive design produces spaces, whether individual or communal, that adapt to contextual climates to create optimal living settings. In this study, a typical house in south-west Nigeria was investigated to exam its thermal performance under the existing climate. Dynamic simulations of the house

allowed thermal comfort conditions to be assessed, and by generating future climate scenarios for the same region it was also possible to estimate future comfort conditions in the house. Finally, some passive design alterations to the house were made and then the impacts of these changes on thermal comfort for current and future climates were investigated.

### **Nigeria and Climate Change**

Nigeria is a west-African country, and is the most populous country in Africa (CIA, 2015). It is also Africa's largest economy, presenting a platform for advancement in all sectors. Presently, it seems that there is still much room for investigations into climate change in Nigeria. AMCEN (2011) stated that Nigeria is the fourth highest emitter of carbon dioxide globally. Therefore, the country is important in discussions that consider the roles that African countries must play towards combating climate change. According to the CIA (2015), Nigeria is a party to the Climate Change-Kyoto Protocol, which was "*...an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its parties by setting internationally binding emission reduction targets*" UNFCC (2014).

National awareness about climate change is being encouraged in Nigeria, and regions of the country are being incentivised about taking steps towards mitigating climate change. From reports of present and predicted floods in southern Nigeria, it is apparent that the country's coastal regions are at risk (AMCEN, 2011). Other predictions state that the increased flooding will be accompanied by droughts in rural areas, which may trigger rural-urban migration. Consequently, there will be rapid urbanisation, which implies higher levels of poverty, inadequate infrastructure and housing. South-western Nigeria's climate change can be addressed partly from the platform of architecture, by promoting the use of green and climate-responsive housing solutions in the region (AMCEN, 2011).

### ***South-western Nigeria's geography, climate and housing***

South-western Nigeria lies along the country's western coastline, bordered by the Atlantic Ocean (see Figure 1). The region comprises of six states, namely: Oyo, Ogun, Lagos, Osun, Ekiti and Ondo. The population of the region has been estimated at 32.5 million people and they account for about 21% of Nigeria's total population (AOAV, 2014). The Yoruba have dwelt in large urban communities in Nigeria's south-western regions for thousands of years (Laitin, 1986). The south-western Nigerian topography features mainly lowlands. The climate of the region is equatorial and tropical rainforests abound. There is a rainy season, which is caused by the wet south-west winds blowing from the Atlantic. This generally lasts from March till November. The dry season lasts from November till March and is caused by the Harmattan winds, which blow from the northern deserts (My Destination, 2014).

### ***South-western Nigerian housing and climate change***

Against the background of oil flares and waste sites it may seem that housing is a relatively negligible contributor to climate change in the region (AMCEN, 2011). However, national plans towards climate change mitigation emphasise that development takes in to consideration climate-responsive and climate-sensitive growth. When south-western Nigerian housing is studied, definite relationships between housing practices and the climate context can be established. Presently, typical modern and affordable housing available in south-western Nigeria possess a hip and gable roof, while featuring the use of glass sliding or louvered windows, reinforced concrete slabs and columns and metal roofing sheets. In many

such dwellings, the installation of electric appliances, such as air conditioning units or electric fans, and fluorescent tubes among others, are very necessary due to the climatic context (Olaniyan et al, 2013). As this borrowed architecture is climatically unsuitable, occupants resort to using electrically powered mechanical ventilation when indoor air temperatures are high. As such, petrol generators, which release carbon dioxide, are commonly used in the region. Thiele (2013) points out that burning fossil fuels, such as petrol, for energy will accelerate climate change. Accordingly, a large amount of qualitative research has shown that the degree of climate-responsiveness of modern south-western Nigerian housing is relatively low. Presently, there are efforts at understanding the climate responsiveness of housing design in this region objectively, and this study represents one such effort.



Figure 1. South-west Nigeria (source: <http://www.seedbuzz.com/knowledge-center/article/seed-supply-system-for-vegetable-production-at-smallholder-farms-in-southwe>).

## Methodology

### ***Thermal comfort and parametric optimisation***

This study primarily aimed to examine quantitatively thermal comfort and building envelope climate-responsiveness and performance in a typical south-western Nigerian family house. Thermal comfort predictions, derived from the computer modelling software DesignBuilder, were analysed and compared against different building envelope designs (set by tropical design standards). Hence, this study employed the parametric optimisation concept which involves searching for the best possible solution to a problem under the constraints of certain parameters (Lee, Han & Lee, 2016). This study focused on the relationship between air temperature and the building envelope under different climate scenarios, created by a unique specification of building envelope parameters without altering the general model. The operative temperature was considered for thermal comfort, especially as studies have revealed that humidity is generally a minor factor in determining thermal comfort (Mallick, 1996). In addition, the effects on the internal thermal environment due to climate change in south-western Nigeria were also investigated. The ASHRAE 55 adaptive thermal comfort standard served as the bench mark for this analysis. This standard stipulates that for optimum thermal comfort conditions the operative air temperature should be between 23°C and 29°C.

### ***Geographical context and climate of study***

Climatic data were generated by the software Meteonorm (Meteonorm 2015) for the south-western Nigerian city of Ibadan, which is built on seven hills and is approximately 150 km from the Atlantic Ocean. It is geographically located between latitude  $7^{\circ} 20'$  and  $7^{\circ} 40'N$ . The month of March - the warmest month - was chosen for the analysis. Meteonorm was used to generate both current and future weather data files for Ibadan up to the year 2050. Figure 2 shows the annual average temperature, indicating the magnitude of the predicted increase due to climate change.

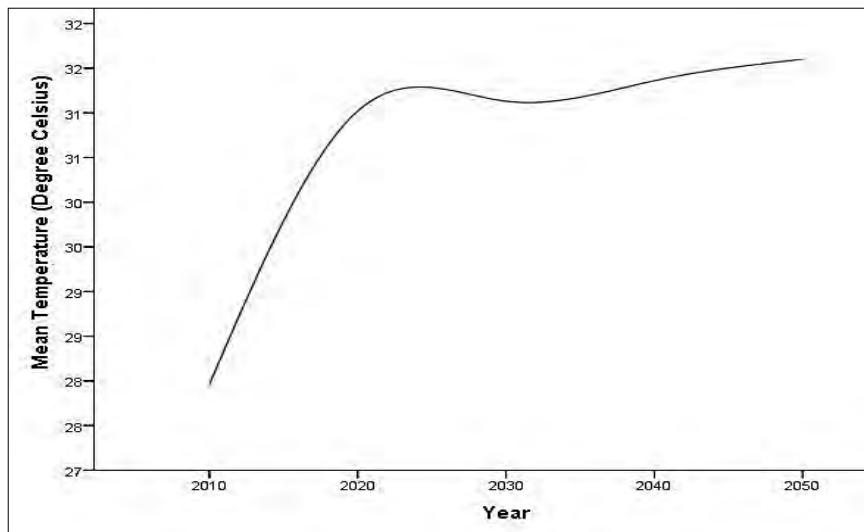


Figure 2. Ibadan's average annual mean air temperature now and up to 2050 (source: Meteonorm).

### ***House and materials***

A typical lower middle-class contemporary low-cost house was modelled using DesignBuilder (see Figure 3). The house had a total floor plan area of  $36m^2$  with a lounge ( $15m^2$ ), dining area ( $11m^2$ ), kitchen ( $11m^2$ ), bathroom ( $10m^2$ ) and two bedrooms (each  $16m^2$ ), and would typically accommodate 4 to 6 people. The base case model consisted of the basic envelope, with external walls made of 230mm cement/plaster mortar blocks; a floor of 126mm reinforced concrete slab with screed; and a pitched, uninsulated roof with a metal covering. No HVAC systems were used. Meteonorm climatic files were exported in an .epw format to DesignBuilder and indoor air temperature values were derived from the simulation analyses. Simulations based on the climatic contexts on a day during the hottest month of the year (March) were produced.

Based on weather data generated by Meteonorm, future weather conditions for south-western Nigeria over the next 35 years were generated to compare thermal comfort parameters now and in the future. The results of the simulation analyses show a rise in outside dry bulb temperature levels (see Figure 2). The building envelope performance was optimised for present (1991-2010 Meteonorm dataset) and future (2050 Meteonorm data set) climates. The month of March, the warmest month, was chosen for analysis. The validity of the DesignBuilder weather data values were checked against field measurements of external temperatures made by Adunola (2014) in Ibadan (Figure 4), and the agreement was satisfactory.



Figure 3. Base case model – floor plan and 3D model.

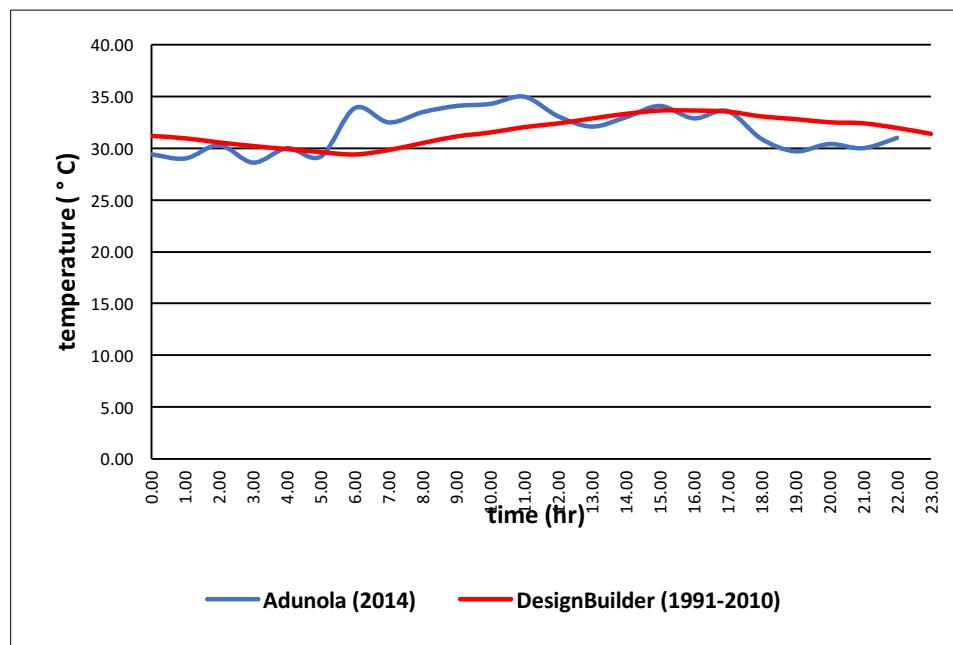


Figure 4. Validation of external temperature data for March (source: author's data analysis; Adunola, 2014).

## Results

A parametric analysis for the walls, floor and roof constructions was undertaken for the hottest month of March. This study considered that thermal comfort had been established when the operative temperature (average of indoor air and mean radiant temperature) was within the comfort zone ( $23^{\circ}\text{C}$  -  $29^{\circ}\text{C}$ ). For walls, Figure 5 shows that for the current SW Nigerian climate, hollow heavyweight concrete walls performed better than natural adobe or stone walls. However, operative temperatures with heavyweight concrete walls were still outside of the comfort zone (the shaded area in Figures 5 to 8).

Two composite floor types were assessed: reinforced concrete slab and concrete slab with timber joists. The reinforced concrete floor promoted temperatures closest to the comfort zone (see Figure 6). Here, during the hottest periods of the day (12:00 noon to 17:00) temperatures were still outside the thermal comfort range.

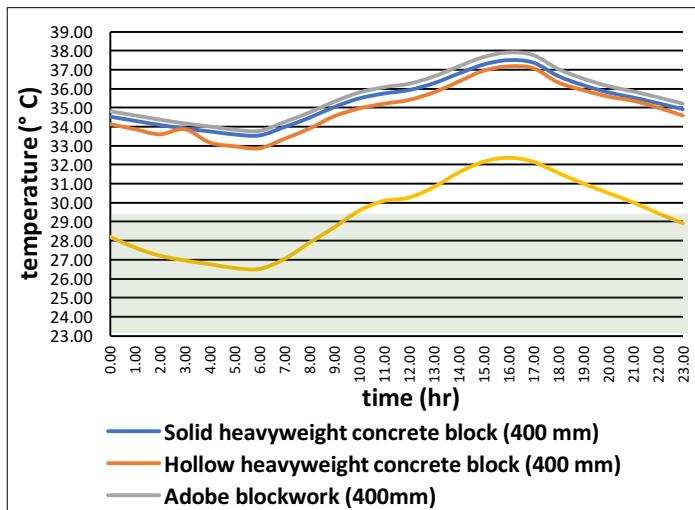


Figure 5. Hourly mean indoor operative temperature for different wall materials in March.

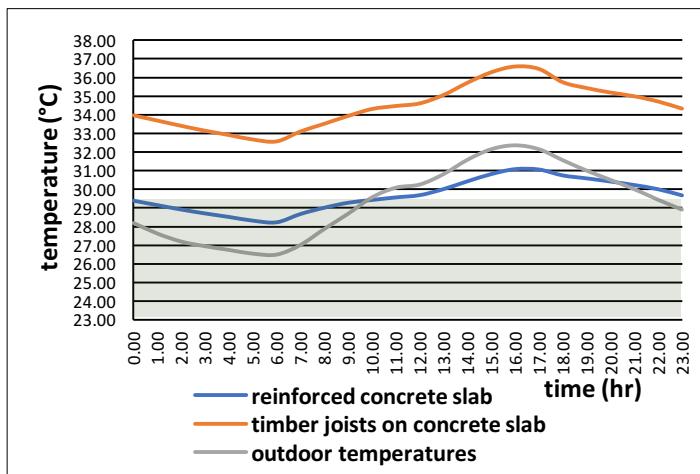


Figure 6. Hourly mean indoor operative temperature for different floor materials in March.

Two roofs were examined to optimise the roof performance. These were the hardwood-framed pitched roof and hardwood-framed flat-roof. With the hardwood-framed pitched roof, all the diurnal temperature ranges fell within the comfort range (see Figure 7). Finally, comparisons between the basic dwelling model for present and future climates revealed that the operative temperatures were outside of the thermal comfort range in both instances. However, the optimised building envelope delivered thermal comfort in present and future climates (see Figure 8 (a) and (b)).

### **Discussion**

The best-performing heavyweight hollow concrete block wall contradicts the claims of many studies that promote adobe walls for humid tropical climates (Tessema et al, 2013; Osasona, 2007). Optimisation of the floors also validated concrete as a suitable material for the climate as opposed to the timber material promoted by some studies (Atkinson 1950). For the roofs, a pitched roof undoubtedly performed best, as has been found by previous research (Jiboye & Ogunshakin, 2010). The interesting observation was the fact the concrete walls performed

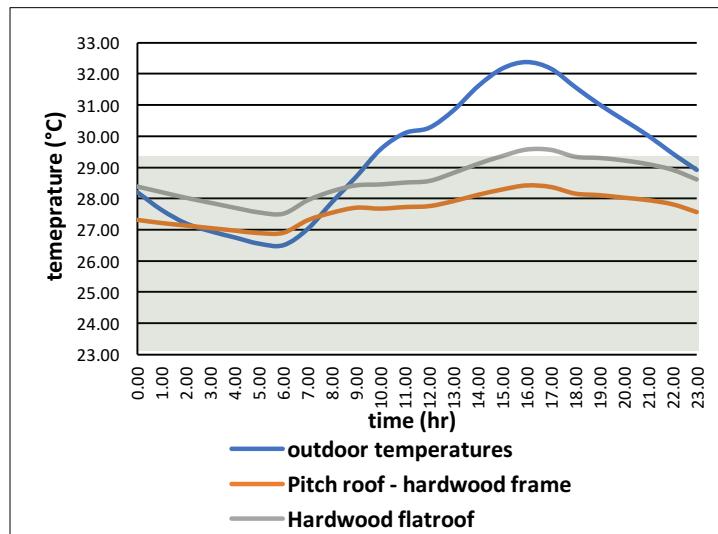


Figure 7. Hourly mean indoor operative temperature for different roofs in March.

better than adobe walls. Similarly, concrete represented a better option compared to timber, another indigenous building material. Therefore, there seems to be a limit to how much indigenous construction can be integrated effectively with modern construction.

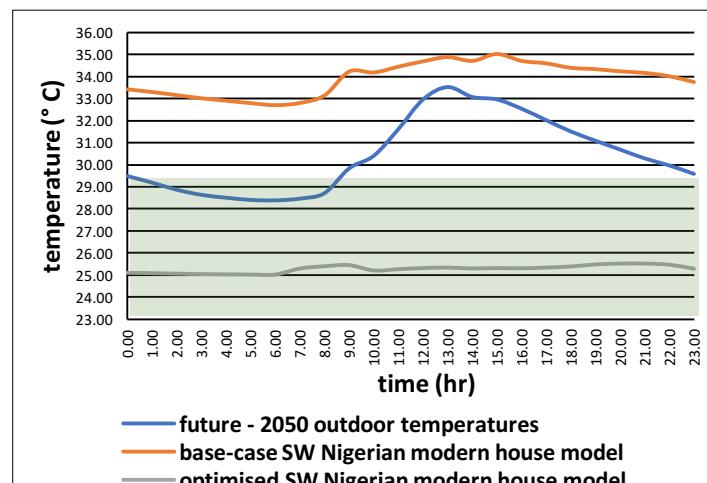
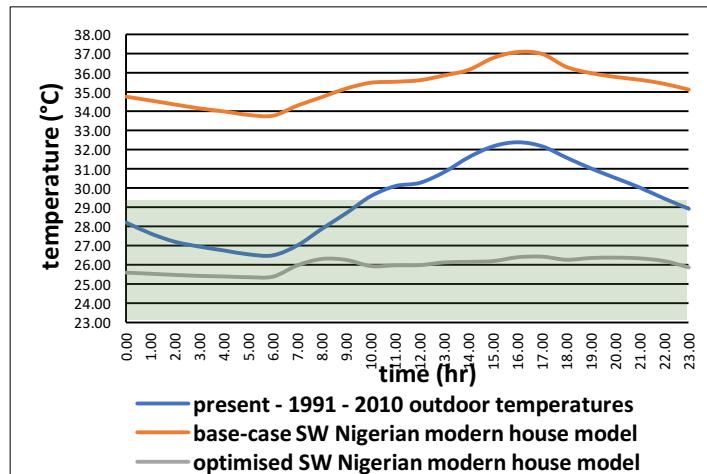


Figure 8. Comparison between optimised and unoptimized versions of SW Nigerian modern house model for present (top graph) and 2050 (bottom graph) climates.

## Conclusions and recommendations

Based on the results, it can be concluded that optimising a dwelling's envelope is a promising way of improving indoor thermal comfort for the present south-west Nigerian climate. Furthermore, the optimisation analyses indicate the ability of the building envelope to adapt to future climates. However, this study has only explored the relationship between temperature and the building envelope within the south-western Nigerian climate presently and in the future. Therefore, there is a need for more investigations into the effects of building envelope optimisation on other indoor environmental parameters, such as natural ventilation and air quality, in present and future climates.

## References

- ADUNOLA, A. O. (2014) Evaluation of urban residential thermal comfort in relation to indoor and outdoor air temperatures in Ibadan, Nigeria. *Buildings and Environment* [Online] 75, pp.190-205 DOI: <http://dx.doi.org/10.1016/j.buildenv.2014.02.007> [Accessed: 24/5/16]
- AMCEN. (2011) *Addressing Climate Change Challenges in Africa; A Practical Guide Towards Sustainable Development.* [Online] Available from: [http://www.unep.org/roa/amcen/docs/publications/guidebook\\_ClimateChange.pdf](http://www.unep.org/roa/amcen/docs/publications/guidebook_ClimateChange.pdf) [Accessed: 7/11/16]
- AOAV. (2014) *The Violent Road: Nigeria's South West.* [Online] Available from: <http://aoav.org.uk/2013/the-violent-road-nigeria-south-west/> [Accessed: 21/7/14]
- ATKINSON, G. A. (1950) African Housing. *African Affairs* 49(196) pp.228-237
- CIA. (2015) *The World Factbook – Nigeria.* [Online] Available from: <https://www.cia.gov/library/publications/the-world-factbook/geos/ni.html> [Accessed 30/9/15]
- IJEOMA, S (2012) *Nigeria & climate change adaptation*, International Society of Sustainability Professionals Insight, May, p 1-6.
- JIBOYE, A. D. & OGUNSHAKIN, L. (2010) The Place of the Family House in Contemporary Oyo Town, Nigeria. *Journal of Sustainable Development* 3(2), pp.117-128.
- JOHNSON, C., TOLY, N. & SCHROEDER H. (eds.) (2015) *The Urban Climate Challenge: Rethinking the Role Of Cities in the Global Climate Regime.* New York: Taylor and Francis.
- LAITIN, D.D. (1986) *Hegemony and Culture: Politics and religious Change among the Yoruba.* Chicago: University of Chicago Press.
- LEE, K. S., HAN, K. J. & LEE, J. W. (2016) Feasibility Study on Parametric Optimisation of Daylighting in Building Shading Design. *Sustainability* 8.
- MALLICK, F. H. (1996) Thermal Comfort and building design in the tropical climates. *Energy and Buildings* 23, pp.161-167.
- METEONORM (2015) <http://meteonorm.com/en/> [Accessed: 14/9/15]
- MY DESTINATION. (2014) "Global Home: Nigeria: South West Region Guide. <http://www.mydestination.com/nigeria/regionalinfo/6182976/south-west-region> [Accessed: 21/7/14]
- NIANG, I., RUPPEL, O.C., ABDRABO, M.A., ESSEL, A., LENNARD, C., PADGHAM, J., and URQUHART, P. (2014): "Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects". Fifth Assessment Report of the IPCC [Barros, V.R., et al (eds.)]. Cambridge University Press, pp. 1199-1265.
- OLANIYAN, S. A., AYINLA, A.K. & ODETOYE, A.S. (2013) Building Envelope vis-à-vis indoor thermal discomfort in Tropical Design: How Vulnerable are the Constituent Elements? *International Journal of Science, Environment and Technology* 2(5), pp. 1370-1379
- OSASONA, C.O. (2007) *From Traditional Residential Architecture to the Vernacular.* <http://www.obafemio.com/uploads/5/1/4/2/5142021/nigerianarchitechture.pdf> [Accessed: 9/7/15].
- TESSEMA, F., TAIPALE, K. & BETHGE, J. (2009) *Sustainable Buildings and Construction in Africa.* Germany: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) Press.
- THIELE, L. P. (2013) *Sustainability.* Cambridge: Polity Press.
- UNFCCC. (2014) *Kyoto Protocol.* [Online] Available from: [http://unfccc.int/kyoto\\_protocol/items/2830.php](http://unfccc.int/kyoto_protocol/items/2830.php) [Accessed: 9/7/16]



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Impact of Different Watering Strategies on the Cooling Effects of Pavement-Watering during Heat-Waves

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**Abstract:** Pavement-watering is currently being viewed as a promising cooling technique for dense cities seeking short-term climate change adaptation methods. In this regard, the city of Paris has implemented a field experiment since 2013 in order to improve pedestrian's thermal comfort during heat waves, using the city's non potable water network. The campaigns conducted in 2013 and 2014 have demonstrated that pavement-watering has a positive impact on pedestrians' thermal comfort. In 2015 and 2016, different watering strategies were experienced, aiming to reduce the method's water consumption. In 2015, fewer statistically significant events were found in the morning with regard to the previous years, though the air temperature at 1.5m was reduced up to 1.2°C and by 0.6°C on average. Relative humidity and mean radiant temperature were also affected, resulting in a reduction of UTCI-equivalent temperature up to 2.8°C and by 1.2°C on average. Over the summer of 2016, the impact of the new watering strategy remains uncertain, due to several reasons. The impact of that change on the micro-climatic effects of pavement-watering is though discussed and future improvements are proposed.

**Keywords:** Pavement-watering, climate change adaptation, urban cooling, thermal comfort, urban heat island

### Introduction

In order to cope with climate change, cities have to develop innovative methods to deal with heat waves, that are likely to become both more frequent and intense in the upcoming years and that can cause excess mortality of the population (Robine, 2008). In this regard, the city of Paris has shown interest since 2013 in the implementation of a field experiment taking place on rue du Louvre, which aims to determine the effects of pavement-watering on pedestrians' thermal comfort (Hendel, 2015).

Our study is part of that process and proposes the quantification of the cooling effects of *in situ* pavement-watering during heat waves. To that purpose, two weather stations have been installed on rue du Louvre, one case and one control. Over the summers of 2013 to 2015, both the pavement and the road were watered. The campaigns carried out in 2013 and 2014 have demonstrated that pavement-watering leads to a 0.79°C maximal reduction of air temperature (0.31°C on average). Other parameters being also affected, the Universal Thermal Climate Index (UTCI)-equivalent temperature is reduced up to 1.03°C and by 0.42°C on average. In 2015, the watering frequency was reduced in the morning with regard to the previous years, while in 2016, only the road was watered instead of the both the road and the pavement. The purpose of those new watering strategies was to determine whether

pavement-watering cooling effects would still remain significant while reducing the amount of water used by the process.

Unfortunately, a dysfunction of our control weather station in 2016 on rue du Louvre forced us to use another control station, located in the Belleville district in Paris, 4.5 km away from the former. In addition to that, due to overall bad weather conditions in Paris in June and July 2016, almost all of the watered days on rue du Louvre occurred at the end of August, during which weather conditions met our requirements to trigger watering, unlike the previous years during which it mostly occurred during the months of June and July. Between those two periods, the net radiation overall look varies greatly on the Louvre site, leading to additional difficulties in the analysis of the 2016 data.

As a consequence of those two random hazards, the impact of the new watering strategy experienced in 2016 remains unclear. We here present an analysis of the cooling effects of pavement-watering in 2015 using both Louvre weather stations, and also a comparison between 2015 and 2016 using the Louvre case station and Belleville control station. The impact of the chosen watering strategy is then discussed and compared to the results obtained in 2013 and 2014, and further improvements are proposed.

## Methodology

The methodology applied for our field experiment is thoroughly described in Hendel (2015). It is briefly reminded hereafter.

### *Site location*

Local micro-climatic data was measured over the summers 2013 to 2016 on rue du Louvre, a north-south oriented street in the 1<sup>st</sup> and 2<sup>nd</sup> districts of Paris. Control and case weather stations are positioned approximately 200 m apart (see Figure 1). Due to a dysfunction of the Louvre control station in 2016, another control station was used, located in the Belleville district. This control station is located ~4.5 km away from the Louvre site and is positioned in an east-west oriented street. In previous studies (Hendel, 2015 & Hendel et al., 2016), this Belleville station was though used as a case station. For consistency, it will be though referred to as “Belleville control station” hereafter.



Figure 1. Station positions at the Louvre (left) and site locations across Paris' non potable water network (right) (Hendel, 2015).

#### **Watering strategy**

Pavement-watering was triggered if weather conditions met our criteria, based on a three-day Météo-France's forecast. The watering criteria, as well as the heat-wave criteria for Paris, are presented in Table 1.

Table 1. Weather conditions required for pavement watering and heat wave warnings in Paris

Parameter	Pavement-watering	Heat-wave warning level
Minimum air temperature	$\geq 16^{\circ}\text{C}$ (3-day mean)	$\geq 21^{\circ}\text{C}$ (3 consecutive days)
Maximum air temperature	$\geq 25^{\circ}\text{C}$ (3-day mean)	$\geq 31^{\circ}\text{C}$ (3 consecutive days)
Wind speed	$\leq 10 \text{ km/h}$	-
Cloud cover	sunny (< 3 oktas clouds)	-

On watered days, pavement-watering is ensured by the passing by of cleaning trucks using Paris' non-drinkable water, principally sourced from the Ourcq Canal. From 2013 to 2015, approximately 1mm of water was sprinkled every hour from 6:30 to 11:30 (in 2015, every two hours from 9:00 to 13:00, and in 2016, every one hour and a half from 7:00 to 11:30) and every 30 minutes from 2 pm to 6:30 pm on both the pavement and the road. In 2016, only the road was watered.

### Weather stations

A weather station diagram is illustrated on Figure 2. These are placed on the border of the pavement and measure air temperature ( $T_{\text{air}}$ ), relative humidity (RH) and black globe temperature at pedestrian height (1.5 m) as well as wind speed and net radiation at 4 meters above ground level. Instruments were protected from vandalism using a white-painted cage. Measurements were made continuously once every minute and were recorded using local day time (UTC+2).

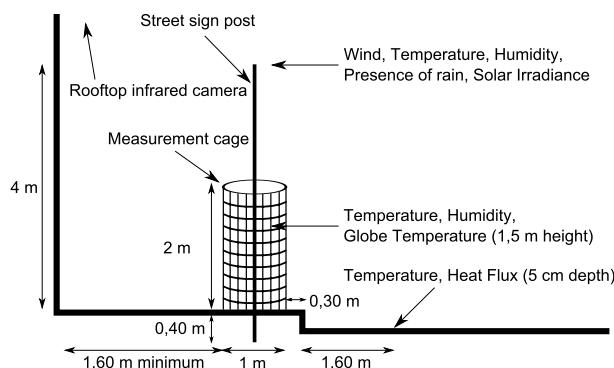


Figure 2. Weather station design and instruments used on rue du Louvre (REF)

### Interpretation method

To estimate the effects of pavement-watering, watered days are compared to reference days, for which weather conditions met our requirements (see Table 1) but watering was not triggered. In Hendel (2015), it was demonstrated that direct comparison between case and control station is not a valid method to determine the field effects of pavement-watering in cities, due to systematic case-control differences on reference days, i.e even when watering is not triggered.

For the analysis of the data, we therefore use a two-sample t-test for each minute to compare the average watered and reference day interstation profiles for each parameter. Therefore, we consider the difference between case and control stations on all reference days and on all watered days, but not the absolute values of the parameters themselves.

Notations chosen for the average profiles as well as the null and alternative hypotheses formulated for the t-test are presented in Table 2. The index “i” stands for the current considered minute while the letter “y” stands for the considered physical parameter for the test. A significance level of 0.05 is used, meaning that if the obtained p-value is lower than 0.05, the null hypothesis is rejected.

Table 2. Notation used for average profiles and hypotheses formulated for the t-test

Average watered profile	$X_i^{\text{wet}} = \langle y_i^{\text{case}} - y_i^{\text{control}} \rangle_{\text{all watered days}}$
Average reference profile	$X_i^{\text{dry}} = \langle y_i^{\text{case}} - y_i^{\text{control}} \rangle_{\text{all reference days}}$
Null hypothesis	$X_i^{\text{wet}} - X_i^{\text{dry}} \geq 0$
Alternative hypothesis	$X_i^{\text{wet}} - X_i^{\text{dry}} < 0$

Also, the mean radiant temperature ( $T_{\text{mrt}}$ ) (used to characterize the ambient radiative environment) was estimated from the measured parameters following the ASHRAE method (ASHRAE. 2001). To estimate the benefits of pavement-watering on pedestrians' thermal comfort, the UTCI is calculated using the simplified Bröde algorithm (Bröde. 2009).

## Results

Effects of pavement-watering on the air temperature in our different case studies are illustrated on Figure 3. All reference days from 2013 to 2016 were used (namely 28) for each analysis. Fig. a represents the effects of the 2015 strategy using Louvre stations (9 watered days in 2015), fig. b using Louvre case and Belleville control stations, and fig. c using Louvre case and Belleville control stations for the 2016 watering strategy (9 watered days in 2016).

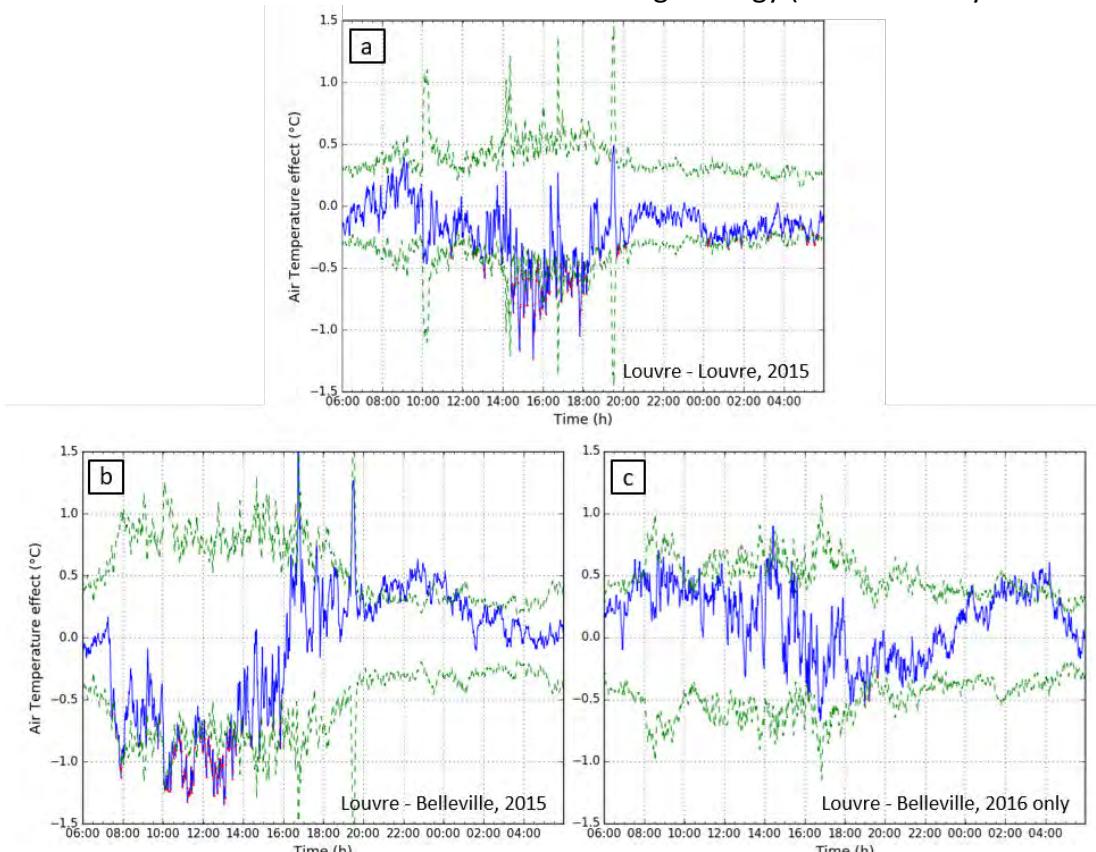


Figure 3. Average watering effects on the air temperature for the Louvre case and control stations over the summers of 2015 (a), for the Louvre case and Belleville control stations in 2015 (b) and for 2016 only (c)

Blue lines represent the average effect of watering while green dotted lines represent the margin of error of the t-test. Beyond this margin are statistically significant (stat. sign.) events, represented with red dots, for which  $p\text{-value} < 0.05$ , meaning that we are at least 95% confident that we wouldn't obtain such a value if the null hypothesis were correct.

On figure 3a, we notice that the impact of pavement-watering in 2015 is manifest. Mostly negative stat. sign. changes are exhibited for the air temperature, i.e the environment is made cooler thanks to watering. Though effects of watering are perceived throughout the whole day, maximum effects are experienced roughly from 14:00 to 19:00.

As compared to the effects obtained over the summers of 2013 and 2014 (Hendel et al., 2016), we notice that the cooling effects of watering in the morning seem to be lessened in 2015, due to the change of the watering frequency (once every 2h in 2015 against once every hour before). Indeed, fewer stat. sign. events are detected from 9:00 to 12:00.

On figure 3b, Belleville control station was used to analyse the 2015 data in order to give better insight of the impact of this analysis method on our results. On this figure, we note that the amplitude of maximum stat. sign. effects are marginally increased, which supports the hypothesis that the watered area on the Louvre site may influence the dry area, as stated in Hendel (2015). To address that issue, new analyses shall be conducted using a matched-pairs t-test for example. Nevertheless, only few stat. sign. events are detected, unlike what is seen on fig. 3 a. This can partially be attributed to the enlargement of the margin of error for the t-test, due to the major differences in insolation patterns between those two stations as compared to both the Louvre stations, all things equal otherwise. Solar irradiance on the Louvre stations and on Belleville control station is presented on Figure 4.

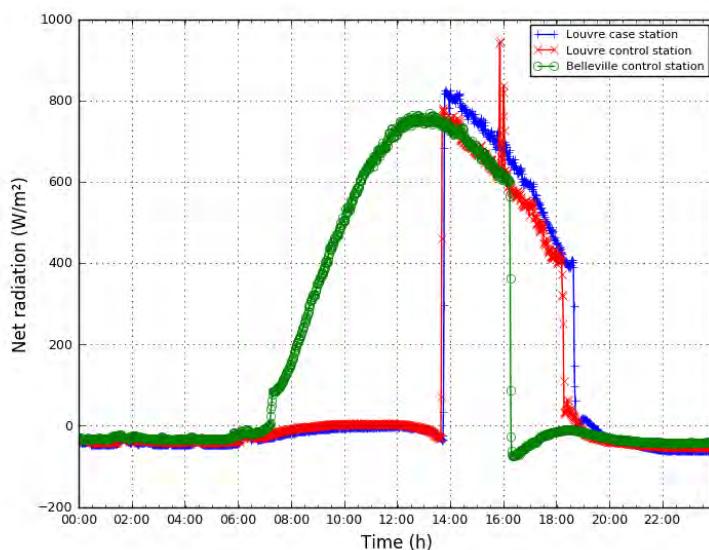


Figure 4. Solar irradiance at Louvre stations and at Belleville control station on the 6<sup>th</sup> of June 2015

On Figure 4, we notice that solar irradiances between the Louvre stations are highly consistent with each other, unlike the Belleville control station. The Belleville station being located in an east-west oriented street, in June, it is illuminated from 8:00 whereas illumination starts at 14:00 on the Louvre. In the afternoon, Belleville and Louvre stations are shaded at respectively 16:00 and 18:00. As a consequence, though figures 3a and 3b are obtained using the same data (only different control stations), the noticeable impact of watering appears at two different moments, namely roughly from 14:00 to 18:00 for fig. 3a and from 10:00 to 14:00 for fig. 3b.

Finally, concerning figure 3c, the impact of watering in 2016 is seemingly less important than what is observed on figure b for 2015 using the same stations. We indeed find out that almost no stat. sign event is detected. This might be the consequence of the use of the Belleville control station (leading to an enlargement of the margin of error with regard to the analysis conducted with both Louvre stations, as previously seen) as well as of the impact itself of watering the road only. Also, most of the watered days occurred in June/July from 2013-2015, while it mostly occurred in August in 2016, where solar irradiance is quite different from the beginning of the summer.

Average and maximum values of stat. sign. events in each case are summarized in Table 3, duration and hour of occurrence of those events are exposed in Table 4, and finally, p-value and mean effect of a 24h t-test are shown in Table 5.

Table 3. Average and maximum values of stat. sign. effects of pavement watering for 2016 and for 2015 using Louvre-Belleville crossed stations, and using Louvre stations only

Parameter	2016 (Louvre case, Belleville control)		2015 (Louvre case, Belleville control)		2015 (Louvre case and control)	
	mean	max	mean	max	mean	max
T <sub>air</sub>	-0.44°C	-0.55°C	-0.81°C	-1.08°C	-0.57°C	-1.23°C
RH	+2.29%	+4.23%	+2.61%	+5.08%	+1.87%	+3.8%
T <sub>mrt</sub>	-1.52°C	-15.3°C	-7.92°C	-12.7°C	-1.39°C	-8.92°C
UTCI	-0.97°C	-3.61°C	-2.46°C	-3.52°C	-1.16°C	-2.84°C

Table 4. Duration of stat. sign events and occurrence hour of maximum stat. sign. Event for 2016 and for 2015 using Louvre-Belleville crossed stations, and for 2015 using Louvre stations only

Parameter	2016 (Louvre case, Belleville control)		2015 (Louvre case, Belleville control)		2015 (Louvre case and control)	
	duration (h/d)	h. of max	duration (h/d)	h. of max	duration (h/d)	h. of max
T <sub>air</sub>	0.15	19:00	3.22	10:12	3.36	15:30
RH	5.52	15:05	6.93	10:24	4.80	15:30
T <sub>mrt</sub>	5.52	16:36	1.50	12:59	4.2	17:50
UTCI	0.9	16:36	0.85	11:24	2.03	17:50

Table 5. p-value and average 24h stat. sign. effects for 2016 and 2015 using Louvre-Belleville crossed stations, and for 2015 using Louvre stations only

Parameter	2016 (Louvre case, Belleville control)		2015 (Louvre case, Belleville control)		2015 (Louvre case and control)	
	p-value	mean	p-value	mean	p-value	mean
T <sub>air</sub>	-	-	-	-	0.0236	-0.20°C
RH	0.018	+0.65%	0.0093	+1.90%	0.0018	+0.77%
T <sub>mrt</sub>	-	-	0.0219	-4.28°C	0.0300	-0.48°C
UTCI	-	-	-	-	not stat. sign.	not stat. sign.

In Table 3, we notice same order of magnitude for stat. sign. events for 2015 between the two analyses, except for mean effects on mean radiant temperature and UTCI, much greater when using Belleville control station. This can be explained when looking at Table 4, where we notice that durations of stat. sign. events are much smaller when using Belleville control station. As seen before, in this configuration, the impact of watering is only detected in the morning. Since fewer stat. sign. events are detected using Belleville control station, mean values are thus brought closer to maximum events values, and tend to increase as a consequence.

Concerning 2016, for the same reason we observe similar effects in Table 3 as compared to 2015. Nevertheless, in Table 4, we note that stat. sign. events for 2016 last less than an hour, except for relative humidity and mean radiant temperature, which happen to be greatly influenced by watering. We therefore conclude that the impact of watering in 2016 is extremely tenuous.

Finally, in Table 5, we observe the 24h average effect of watering and the associated p-value. Empty cells mean that no 24h-average effect was found, and “not stat. sign.” mean that a cooling effect was indeed found but the associated p-value were greater than the confidence interval (0.05). In 2015 using both Louvre stations, a stat. sign. value is found for each parameter, meaning that watering has a great impact of the environment since it is perceived on a 24h average. With Belleville control station, no stat. sign. effects were found for the air temperature and the UTCI. For 2016, no stat. sign. effect was found for the mean radiant temperature either.

## Conclusion

Different watering strategies were conducted in 2015 and 2016 compared to 2013 and 2014. The campaigns carried out in 2013 and 2014 have demonstrated that watering the road and the pavement lead to a reduction of UTCI-equivalent temperature up to 1.03°C and by 0.42°C on average.

In 2015, watering frequency was reduced in the morning with regard to the previous years. The analysis of this data showed overall equivalent results, with a reduction of the UTCI equivalent temperature up to 1.23°C and by 0.57°C on average. Nevertheless, in the morning, fewer statistically significant events were found, meaning that this new watering frequency do have a small impact on the cooling effects exhibited thanks to pavement watering.

Those results were also analysed using a control station located elsewhere. Analysis revealed effects with the same order of magnitude, but a deterioration of the significance level, leading to the detection of much fewer statistically significant events. This observation can be attributed to the poor match of solar irradiances between the meteorological stations used.

Finally, the latter analysis was compared to the 2016 watering strategy, where only the road was watered, in order to reduce the method’s water consumption. Almost no stat. sign. effects were found for this case. Given the difficulties encountered in 2016, it is complicated to conclude if the watering strategy itself is inefficient, or if those results are the consequence of multiple factors. Indeed, using the Belleville control station instead of the Louvre’s has proven that it lessens the average detected effects and their duration. Also, the watered days in 2016 occurred in August whereas it mostly occurred in June and July before. The insolation between those two periods may vary, which has its importance on our comparison. Finally, given that the station is placed on the pavement, the strategy itself is expected to have a little impact on the results.

In any case, given the impact on the 2015 data on the results using the Belleville control station, using two stations with such a poor solar irradiance match seems to be unappropriate.

To better quantify the effect of the 2016 strategy, future campaigns will still focus on the reduction of the water consumption of pavement watering. Future results will be added to those already existing, leading to better statistics for our analyses.

## References

- ASHRAE (2001). ASHRAE Fundamentals Handbook 2001. SI Edition ed. American Society of Heating, Refrigerating, and Air-Conditioning Engineers.
- Bröde, P. (2009). UTCI Fast Calculation Script.
- Hendel, M. (2015). Pavement-Watering in Cities for Urban Heat Island Mitigation and Climate Change Adaptation: A Study of its Cooling Effects and Water Consumption in Paris. PhD. University Paris Diderot Paris 7
- Hendel, M., Gutierrez, P., Colombert, M., Diab, Y., and Royon, L. (2016). Measuring the effects of urban heat island mitigation techniques in the field: Application to the case of pavement-watering in Paris. *Urban Clim.*, vol. 16, pp. 43–58
- Robine, J.-M., S. L. K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J.-P. Michel, and F. R. Herrmann (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes rendus biologies* 331(2), 171–178.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Formulating a methodology to study adaptability in buildings to climate-change: climate-responsive adaptability in Indian conditions**

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**Abstract:** India is famous for its diversity, and is the identified high-risk of climate change. The diversity in climatic zones makes it a challenge in identifying any adaptation measures, as no one-solution would fit all. Climate-change would put the existing habitations to withstand changes in the periodicity, occurrence, and intensity in temperature, humidity, rainfall, and wind, all of which have originally influenced the design of vernacular buildings. Studying building adaptability, in terms of design and material configuration could provide a valid basis to verify the inherent preparedness of a habitation to impending climate-change and in devising active measure to mitigate vulnerability. The main objective here is to formulate a methodology to study adaptability of buildings, focusing on their climate-responsiveness. This would include the design of the building in response to the specific climate, geographic location, and the material configuration defining the building elements. The focus would be on passive and/or naturally ventilated dwellings, with an assessment on current/future demands on energy for maintaining thermal comfort. Besides prospective variations in climate classification in view of climate change, the proposed methodology would attempt to map the climate change repercussions in the physical manifestations and comfort requirements of a building for various climate zones.

**Keywords:** Climate change, Building adaptation, Climatic zone, Building comfort requirement

### **Introduction**

Climate change is imminent, on going, expected to occur more rapidly, and unpredictably than earlier expected. It is defined as the change in state of climate, recognized by changes in the different climatic parameters that persist for a long duration, due to either natural processes or external forces. Human induced reasons such as burning of fossil fuel, deforestation etc. causes global warming. It is the regional variation of climate due to rise in temperature, acting globally (Sands 1992), (V. Ramaswamy 2006). The independent analyses carried out by NASA and the National Oceanic and Atmospheric Administration (NOAA) has recorded the warmest surface temperatures during 2016, since 1880. The temperatures in 2016 were 0.99 degree Celsius warmer than the global average of mid-20<sup>th</sup> century mean. The entire year with eight of the twelve months were the warmest on the records. The average surface temperature of earth has increased about 1.1 degree Celsius since late 19<sup>th</sup> century. This is largely due to the various human driven emissions into the atmosphere (GISTEMP Team 2016),(Hansen et al. 2010) (IPCC 2014).

### **Climate change and habitations**

Climate change is affecting the habitations worldwide. A study on five bird species of south western United States shows that there is high risk of lethal dehydration due to increase in hourly temperature (Albright et al. 2017). The health of human beings is also highly sensitive

to the change in weather patterns and various aspects of climate. Habitations, particularly in the developing countries, are most prone to climate change directly as well as indirectly. If the variations in climatic factors such as temperature, humidity, precipitation or the occurrences of heat waves, drought, flood, fire etc. are the direct effects, indirect effects include the crop failures, shifting patterns of diseases, population migration due to prolonged drought etc. (Mertz et al. 2009).

### **Climate change and Built environment**

Built environment is also undergoing significant impact due to climate change. Based on the climatic zone, there will be considerable variation in energy use and energy demand. There will be changes in the use pattern of heating and cooling equipment, which can alter the economy pattern as well. There will be probable sways on the comfort levels of the occupants based on the changes in weather parameters. Climate-change would put the existing buildings to withstand changes in the periodicity, occurrence, and intensity in temperature, humidity, rainfall, and wind, all of which have originally influenced the design of vernacular habitations. However, many researches discuss the impact of buildings on climate change, such as air pollution, CO<sub>2</sub> emission, urban heat island, surface run-off and change in wind direction, very few discuss on the other way around. Nevertheless, a test was carried out on a small office building to show the scope of using building performance simulation tools in assessing the potential impact due to climate change. The prospective alterations in comfort levels, energy use and demand, effects on heating and cooling equipment, emission impacts, etc. is being discussed (Drury B. Crawley 2003).

### **Building adaptation**

According to James Douglas, “building adaptation include any work to a building over and above maintenance to change its capacity, function or performance”. Adaptability is the key attribute of adaptation where a building’s ability to absorb any scale of change. Building adaptation can be in different ways based on the purpose; reuse of space according to human needs, otherwise called adaptive reuse, the transformation of buildings due to anticipated changes or flexibility of built spaces to changing needs (Douglas 2006).

### **Methodology**

Building adaptation can be in two ways, spontaneous or involuntary and unsupernatural or voluntary. The term ‘Building adaptation’ in this study, is any unsupernatural or voluntary intervention to adjust a building to suit the changing conditions with respect to climate. This would test the ability of the built environment to withstand higher temperatures, drier or wetter seasons, and altered wind-regimes in providing favourable living conditions, and test short and long-term structural and durability resilience. Studying building adaptability, in terms of design and material configuration could provide a valid basis to verify the inherent preparedness of a habitation to impending climate-change and in devising active measures to mitigate vulnerability. The current scope is limited to predominantly vernacular dwellings, with an assessment on current/future demands on energy for maintaining thermal comfort. Even though the vernacular dwellings are more attuned to prevalent climates, the methodology is expected to be applicable to modern dwellings as well.

India is famous for its diversity, and is the identified high-risk of climate change (IPCC 2014). The diversity can be clearly seen in the various zones identified such as, hot and dry,

warm and humid, moderate, cold and sunny, cold and cloudy, and composite climates (Nayak & Prajapati 2006). The diversity in climatic zones makes it a challenge in identifying any adaptation measures, as no one-solution would fit all. The Table 1 below provides the general adaptation techniques available, with respect to the variation in climatic factors that form the basis for further studies. This is prepared in view of the probable changes occurring to the climatic factors of different climatic zones as mentioned in the other tables of this study. For example, a region belonging to the moderate climatic zone may shift to warm and humid climate. Then, the mechanisms adopted for comfort may become inadequate. The Table 1 discusses the potential adjusting mechanisms to achieve comfort in terms of occupant physiology, clothing, and buildings.

In this research, the authors are also trying to develop the prospective variations in the existing climatic zones of the country, due to climate change. It include the variations in the physical manifestations of a building, changes in the existing climate classification, and change in the building comfort requirement features during both heat loss and heat gain. The tables 2, 3 and 4 are adapted from the book chapter in press for the Encyclopaedia of Sustainable Technologies by Elsevier. The Table 2 shows both climate classification and climate change implications in physical manifestations of the buildings, corresponding to the increase and decrease in mean monthly temperature. The Table 3 and Table 4 shows the climate classification along with the building comfort requirement features, to resist heat gain and to promote heat loss respectively during the change in mean monthly temperatures. However, a reclassification of the climatic zones is challenging, as it is uncertain, but it forms the basis for this study of building adaptation due to climate change. This would include the design (and geometry) of the building in response to the specific climate and geographic location, and the (local) material configuration defining the building elements (walls, roof, fenestration, etc.) that determines the thermal performance of the building in appropriately regulating indoor thermal comfort.

## **Discussion**

We can see that, hot and dry zone requires a revision in classification, as the conditions are intensified due to increase in mean monthly temperature. Both cold & sunny and cold & cloudy zones require a revision in classification as the conditions are aggravated due to decrease in mean monthly temperature. The study observes that due to increase in mean monthly temperature, the regions belonged to moderate and composite zones has shifted to warm and humid zone, whereas the regions belonged to cold & cloudy and cold & sunny has shifted to moderate zone. There will be corresponding modifications to the building physical manifestations and the comfort requirements due to heat loss and heat gain.

## **Conclusion**

Climate change is occurring unpredictably worldwide. The different climatic zones in India are also facing severe changes on the various climatic factors such as temperature, humidity, wind, precipitation, and solar radiation. Therefore, it is necessary to add building adaptation as a major requirement among the other functional features of a built environment. The present study has looked at the role of building adaptation in the scenario of climate change. It has formulated a methodology to study the adaptability of buildings focusing on climate responsiveness. It has brought in, the prospective variation of existing climatic zones, with the modifications in physical expressions of a building along with the building comfort requirements, to both resist heat gain and promote heat loss.

Table 1: Adaptation techniques available with respect to the variation in climatic factors

Climatic factors with variation		Occupant Physiology/psychology	Clothing	Buildings
Temperature	High	Behavioural thermoregulation	Insulated, loose-knit, unlined/half lined, light colored fabric with low clo value	Mechanical air conditioning, evaporative cooling, fan or wind induced ventilation, natural ventilation
	Low	Increase metabolic rate to maintain warmer skin temperature	Close-knit, thicker weaves, lined, dark colored, tight-fit fabric with high clo value	Natural ventilation, mechanical heating, passive solar heating
Relative humidity	High	Lessen activity density	Breathable, loose-fit fabric with low clo value	Mechanical air conditioning, fan or wind induced ventilation, natural ventilation, dehumidifiers
	Low	Increase sweating capacity	Close-knit, lined, tight-fit fabric	Natural ventilation, humidifiers
Wind	High	Control room openings	Close-knit, thicker weaves, lined fabric with high clo value	Natural ventilation
	Low	Control room openings	Breathable, loose-fit, loose-knit fabric with low clo value	Fan induced ventilation
Precipitation	High	Mechanical shielding	Water repellent fabric with low clo value	Shading devices
	Low	Less shielding		Rain water harvesting
Solar radiation	High	Mechanical shielding	Breathable, more skin covered clothing with high clo value	Shading devices
	Low	Less shielding	loose-fit, loose-knit fabric with low clo value	Increased openings

Table 2: Climate change implications in unique physical manifestations of building; adapted from the book chapter in press for the Encyclopaedia of Sustainable Technologies by Elsevier, Aysha and Mani (2017)  
<https://doi.org/10.1016/B978-0-12-409548-9.10202-7>

Climate Classification	Unique physical manifestations	Change in climate classification if;		Change in unique physical manifestations	
		Increase in mean monthly temperature	Decrease in mean monthly temperature	Increase in mean monthly temperature	Decrease in mean monthly temperature
Hot and dry	Insulation of building envelope, massive structure, air locks/lobbies/balconies/verandahs/trees /overhangs	Aggravates (revision in classification required)	Warm and humid		Roof and wall insulation, reflective roof surface, balconies/verandahs, dehumidifiers/desiccant cooling
Warm and humid	Roof and wall insulation, reflective roof surface, balconies/verandahs , dehumidifiers/desiccant cooling	Hot and dry	Moderate	Insulation of building envelope, massive structure, air locks/lobbies/balconies/verandahs/trees/overhangs	Roof/east & west wall insulation, overhangs for east & west wall/trees/fins
Moderate	Roof/east & west wall insulation, overhangs for east & west wall/trees/fins	Warm and humid	Cold and cloudy/ Cold and sunny	Roof and wall insulation, reflective roof surface, balconies/verandahs, dehumidifiers/desiccant cooling	Roof & wall insulation, double glazing, thicker walls, air locks/lobbies, weather stripping, darker colours, /greenhouses/Trombe walls
Cold and cloudy/ Cold and sunny	Roof & wall insulation, double glazing, thicker walls, air locks/lobbies, weather stripping, darker colours, sun spaces/greenhouses /Trombe walls	Moderate	Aggravates (revision in classification required)	Roof/east & west wall insulation, overhangs for east & west wall/trees/fins	
Composite	Roof & wall insulation, thicker walls, dehumidifiers/desiccant cooling, exhausts	Warm and humid	Moderate	Roof and wall insulation, reflective roof surface, balconies/verandahs, dehumidifiers/desiccant cooling	Roof/east & west wall insulation, overhangs for east & west wall/trees/fins

Table 3: Climate change implications in comfort requirements (to resist heat gain); adapted from the book chapter in press for the Encyclopaedia of Sustainable Technologies by Elsevier, Aysha and Mani (2017)  
<https://doi.org/10.1016/B978-0-12-409548-9.10202-7>

Climate Classification	Building comfort requirement features to resist heat gain	Change in climate classification if;		Building comfort requirement features to resist heat gain	
		Increase in mean monthly temperature	Decrease in mean monthly temperature	Increase in mean monthly temperature	Decrease in mean monthly temperature
Hot and dry	Decrease exposed surface area, air exchange rate and increase thermal resistance, thermal capacity, surface reflectivity, buffer spaces and shading	Aggravates (revision in classification required)	Warm and humid		Decrease exposed surface area and increase thermal resistance, surface reflectivity, buffer spaces and shading
Warm and humid	Decrease exposed surface area and increase thermal resistance, surface reflectivity, buffer spaces and shading	Hot and dry	Moderate	Decrease exposed surface area, air exchange rate and increase thermal resistance, thermal capacity, surface reflectivity, buffer spaces and shading	Decrease exposed surface area and increase thermal resistance, surface reflectivity, and shading
Moderate	Decrease exposed surface area and increase thermal resistance, surface reflectivity, and shading	Warm and humid	Cold and cloudy/ Cold and sunny	Decrease exposed surface area and increase thermal resistance, surface reflectivity, buffer spaces and shading	Decrease exposed surface area, air exchange rate and increase thermal resistance, thermal capacity, surface absorptivity and buffer spaces
Cold and cloudy/ Cold and sunny	Decrease exposed surface area, air exchange rate and increase thermal resistance, thermal capacity, surface absorptivity, buffer spaces	Moderate	Aggravates (revision in classification required)	Decrease exposed surface area and increase thermal resistance, surface reflectivity, and shading	
Composite	Decrease exposed surface area, air exchange rate and increase thermal resistance, thermal capacity, surface reflectivity, buffer spaces and shading	Warm and humid	Moderate	Decrease exposed surface area and increase thermal resistance, surface reflectivity, buffer spaces and shading	Decrease exposed surface area and increase thermal resistance, surface reflectivity, and shading

Table 4: Climate change implications in comfort requirements (to promote heat loss); adapted from the book chapter in press for the Encyclopaedia of Sustainable Technologies by Elsevier, Aysha and Mani (2017) <https://doi.org/10.1016/B978-0-12-409548-9.10202-7>

Climate Classification	Building comfort requirement features to promote heat loss	Change in climate classification if;		Building comfort requirement features to promote heat loss	
		Increase in mean monthly temperature	Decrease in mean monthly temperature	Increase in mean monthly temperature	Decrease in mean monthly temperature
Hot and dry	Ventilation of appliances, increase air exchange rate and humidity levels	Aggravates (revision in classification required)	Warm and humid		Ventilation of appliances, increase air exchange rate and decrease humidity levels
Warm and humid	Ventilation of appliances, increase air exchange rate and decrease humidity levels	Hot and dry	Moderate	Ventilation of appliances, increase air exchange rate and humidity levels	Ventilation of appliances and increase air exchange rate
Moderate	Ventilation of appliances and increase air exchange rate	Warm and humid	Cold and cloudy/ Cold and sunny	Ventilation of appliances, increase air exchange rate and decrease humidity levels	Reduce shading, utilize heat from appliances and trapping heat
Cold and cloudy/ Cold and sunny	Reduce shading, utilize heat from appliances and trapping heat	Moderate	Aggravates (revision in classification required)	Ventilation of appliances and increase air exchange rate	
Composite	Ventilation of appliances, increase air exchange rate, humidity levels (summer) and decrease humidity levels (monsoon)	Warm and humid	Moderate	Ventilation of appliances, increase air exchange rate and decrease humidity levels	Ventilation of appliances and increase air exchange rate

## References

- Albright, T.P. et al., 2017. Mapping evaporative water loss in desert passernines reveals an expanding threat of lethal dehydration. *Proceedings of the National Academy of Sciences*, 114(9), p.201613625. Available at: <http://www.pnas.org/lookup/doi/10.1073/pnas.1613625114>.
- S. Aysha, Monto Mani, 2017. Adaptation of Buildings to Climate Change. *Encyclopaedia of Sustainable Technologies*, Elsevier. Available at: <https://doi.org/10.1016/B978-0-12-409548-9.10202-7>
- Douglas, J., 2006. *Building Adaptation*, Edinburgh: Butterworth-Heinemann.
- Drury B. Crawley, 2003. Impact of climate change on Buildings. In CIBSE/ASHRAE International Conference 2003, At Edinburgh, Scotland, UK. (University of Strathclyde, Glasgow, Scotland, UK).
- GISTEMP Team, 2016. GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Available at: [www.data.giss.nasa.gov/gistemp/](http://www.data.giss.nasa.gov/gistemp/).

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010. Global surface temperature change. *Rev. Geophys.*, 48(4), p.RG4004. Available at: <http://dx.doi.org/10.1029/2010RG000345>.

IPCC, 2014. Climate Change 2013 - The Physical Science Basis Intergovernmental Panel on Climate Change, ed., Cambridge: Cambridge University Press.

Mertz, O., K. Halsnaes, J. E. Olesen and K. Rasmussen, 2009. Adaptation to Climate Change in Developing Countries. *Environmental Management*, 43(5), pp.743–752.

Nayak, J.K. & Prajapati, J. a., 2006. Handbook on Energy Conscious Buildings. R & D project no. 3/4(03)/99-SEC between Indian Institute of Technology, Bombay and Solar Energy Centre, Ministry of Non-conventional Energy Sources, 4(3), pp.2093–2117.

V. Ramaswamy, M. D. Schwarzkopf, W. J. Randel, B. D. Santer, B. J. Soden, G.L.S., 2006. Anthropogenic and Natural Influences in the Evolution of Lower Stratospheric Cooling. *SCIENCE*, (February), pp.1138–1141.

Sands, P., 1992. The United Nations Framework Convention on Climate Change. *Review of European Community and International Environmental Law*, 1(3), pp.270–277.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Quantifying the Behaviour of Modern and Traditional Construction Systems on the Basis of Thermal Comfort

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**Abstract:** Thermal comfort is crucial to ascertain the energy consumption in buildings and is a key factor for decision-making in the design of sustainable building envelopes. This paper presents a methodology to assess the performance of construction systems quantitatively on the basis of overall yearly thermal comfort. A framework is proposed to deal with the risk from climate change temperature increases in the UK. A dynamic thermal model with five of the most commonly used construction systems for dwellings was chosen for simulation in London, UK, for current, short term, medium term and long-term climate scenarios using the software Designbuilder. The research investigated the effect of thermal mass and insulation thickness on the behaviour of widely used construction systems based on annual thermal comfort. The study reveals that high level of thermal mass and insulation thickness do not necessarily provide maximum comfort hours in high performance construction systems for future climates.

**Keywords:** Climate Change, Thermal Mass, Insulation, Thermal Simulation

### Introduction

Buildings that can respond to future climate change are less likely to be obsolete, and so future thinking in the early design stages of a building is an essential principle of sustainable development. One of the key parameters to decide energy consumption in buildings and, consequently, to determine possible future optimization is the thermal comfort of occupants. The potential impacts of changes in the UK climate on the built environment have become widely recognized, with possibly the most important feature of these changes being the impact of higher air temperature on building thermal performance. Tabatabaei, et al. (2015) considered the importance of alleviating climate change consequences by passive design features to offset temperature rises. The study also recognized that thermally lightweight homes could cause levels of discomfort by creating higher room temperatures. The research work emphasized that masonry houses, with inherent thermal mass, can result in less energy consumption over their lifetime compared to a similarly designed lightweight timber frame house. A study by Orme et al. (2007) indicated that in lightweight well-insulated houses an outdoor temperature of 29°C might cause overheating, with air temperatures of more than 39°C inside the building. The aim of this study is to quantify the thermal response of some wall construction types to climate change risk. Five of the most commonly used wall construction systems for dwellings were chosen, and all met the German Passivhaus (PH)

standard requirements – a standard that can reduce building carbon emissions by up to 80% in the UK (AECB, 2017).

## Methodology

Five common construction systems, including traditional and modern methods of construction (MMC), were selected and configured to achieve a U-Value of  $0.1 \text{ W/m}^2\text{K}$ . These constructions were used to investigate the effect of thermal mass and insulation thickness on comfort levels using the dynamic thermal simulation software DesignBuilder (DB) that employs EnergyPlus as its calculation engine. The admittance factor, i.e. building fabric response to a swing in temperature (CIBSE, 2006) was taken as a thermal mass performance indicator. The selected construction systems meant low, medium and high thermal mass performances were considered. Current and future weather data for London were used to evaluate the behaviour of the construction systems. Future climate data for three timelines (2020, 2050 and 2080) in London were generated by the ‘CCWeatherGen’ morphing procedure (SERG, 2016). CCWeatherGen morphs Chartered Institution of Building Service Engineers (CIBSE) TRY (Test Reference Year) files into future EPW files based on projections from the UK Climate Impacts Programme (UKCIP). EPW is the weather file format used by DB.

## Climate change

Lisq (2006) emphasized that “*the possible impacts of climate change on the building stock being built over the next few decades must be addressed today*”. Figure 1 illustrates the psychrometric charts for London in 2011 and 2080, with the comfort zones shown. These charts demonstrate likely temperature increases as well as likely thermal discomfort.

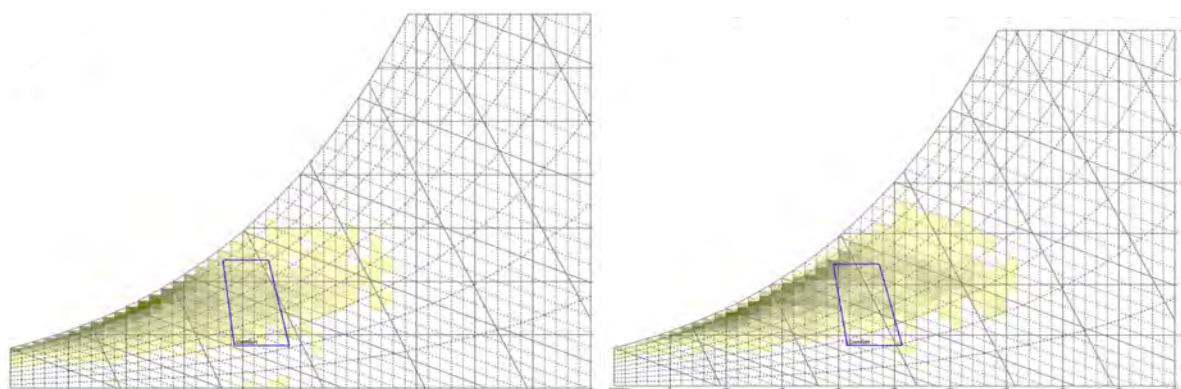


Figure 1. Psychrometric charts for London 2011(left) and London 2080 (right), showing comfort zones

London’s temperatures are expected to increase by around  $5^\circ\text{C}$  between 2011 and 2080, with levels of thermal discomfort also rising. Consequently, temperature increases may increase occupant vulnerability to overheating. Reducing this vulnerability will require improvements in both building energy performance and occupant thermal comfort. This paper examines the impact different construction choices can have in tackling the potential risk of overheating in future dwellings.

## Wall construction types for UK housing

This research considered five commonly used UK wall construction systems. The selection criteria were:

- Recent utilization in the UK housing industry

- Method appropriate for UK housing
- The potential of achieving the Passivhaus standard (set at 0.10 W/m<sup>2</sup>K U-Value)

The building model used for the simulations was a simple, single storey single zone room measuring 8m x 8m x 3.2m high with a centrally located south-facing triple glazed window 2m x 3m wide. The infiltration rate was set at 0.25 air change per hour (AC/H). Mechanical ventilation was considered and U-Values of 0.1 W/m<sup>2</sup>K for the roof and floor and 0.8 W/m<sup>2</sup>K for a triple glazed window were assumed. The wall constructions examined are shown in Table 1.

### **Thermal comfort**

Several studies have proposed a temperature range of 18-26°C as likely to be within the human comfort zone (Gupta & Gregg, 2012). ASHRAE 55-2004 identified thermal comfort as a subjective response and defined it as the '*state of mind that expresses satisfaction with existing environment*' (ASHRAE, 2004). Therefore, it seems that a precise value cannot be assigned to thermal comfort. '*State of mind*' largely depends on residents' perceptions and expectations. ASHRAE-55 is based on a the static heat balance approach, which includes four environmental variables (dry bulb air temperature, mean radiant temperature, relative humidity and air velocity) and two human variables (activity and clothing level). For simplification and quantification purposes, this paper used this standard as a reasonable way to assess the thermal comfort/overheating results.

### **Results and discussion**

DesignBuilder was used to analyse the thermal performance of the wall systems. The generated London weather data used a high emission scenario from the year 2011 until 2080. Predicted levels of total annual discomfort hours are shown in Figure 2 and given in Table 2.



Figure 2. Total annual discomfort hours in London for four climate periods

Table 1. Wall construction systems used for the simulations

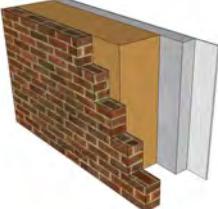
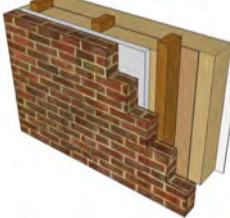
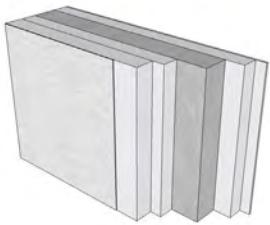
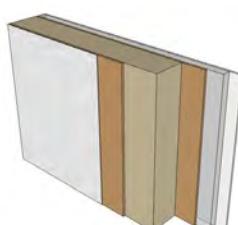
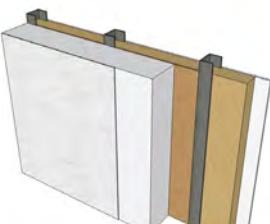
Construction Systems	Details
 Brick and Block BB	From Out to in: 110mm Brick Outer Leaf, 300mm Phenolic Insulation, 100mm Aerated Concrete Block, 10mm Lightweight Plaster Decrement factor (0-1): 0.23; Time Constant (Hrs): 7.7 Admittance ( $W/m^2K$ ): 5.3; U-Value ( $W/m^2K$ ): 0.1 Thickness (mm): 520
 Timber Frame TF	From Out to in: 110mm Brick Outer Leaf, 50mm Air Gap, 140mm Rockwool, 10 mm Plywood, 200mm Rockwool, 12.5mm Plasterboard Decrement factor (0-1): 0.2; Time Constant (Hrs): 3 Admittance ( $W/m^2K$ ): 1.54; U-Value ( $W/m^2K$ ): 0.1 Thickness (mm): 522.5
 Insulating Concrete Formwork ICF	From out to in: 5mm Rendering, 120mm Extruded Polystyrene (EPS), 100mm Extruded Polystyrene (EPS), 160mm Heavyweight concrete, 100mm Extruded Polystyrene (EPS), 12.5mm Plasterboard Decrement factor (0-1): 0.47; Time Constant (Hrs): 5 Admittance ( $W/m^2K$ ): 2.96; U-Value ( $W/m^2K$ ): 0.1 Thickness (mm): 497.5
 Structural Insulated Panel SIP	From out to in: 5mm Rendering, 15mm Softwood board, 200mm Extruded Polyurethane (PUR), 15mm Softwood board, 50mm Air Gap, 12.5mm Plasterboard Decrement factor (0-1): 0.81; Time Constant (Hrs): 2.4 Admittance ( $W/m^2K$ ): 1.16; U-Value ( $W/m^2K$ ): 0.1 Thickness (mm): 297.5
 Steel Frame SF	From out to in: 5mm Rendering, 200mm Extruded Polystyrene (EPS), 10mm Plywood, 90mm Rockwool, 12.5mm Plasterboard Decrement factor (0-1): 0.36; Time Constant (Hrs): 4.9 Admittance ( $W/m^2K$ ): 1.39 ; U-Value ( $W/m^2K$ ): 0.1 Thickness (mm): 317.5

Table 2. Total discomfort hours by year and wall type

Year/Wall	BB	ICF	SF	TF	SIP
2011	2284	2289	2284	2260	2284
2020	2500	2504	2502	2493	2498
2030	2552	2552	2551	2540	2545
2050	2648	2647	2645	2623	2638

### Thermal mass effect

For all periods in London the results from the simulations showed a slight advantage for timber frame (TF) compared to the other wall constructions. Table 1 shows that brick and block (BB) had the highest admittance factor, which demonstrates a high level of thermal mass. However, maximum discomfort hours for most of the times was observed for BB. The behaviour of the steel frame (SF) and insulating concrete formwork (ICF) are almost the same as BB. However, as the climate warms so the performance of the structural insulated panel (SIP) reduced compared to the other systems. The systems all had the same U-Value, and so the thermal mass does not seem to provide a benefit in terms of reducing annual discomfort hours.

### Insulation effect

The study reduced the amount of insulation thickness in each construction (i.e. increased the U-Value) to observe the impact of insulation thickness on the overall performance. Figures 3 to 6 demonstrate the results of this insulation reduction for each construction system.

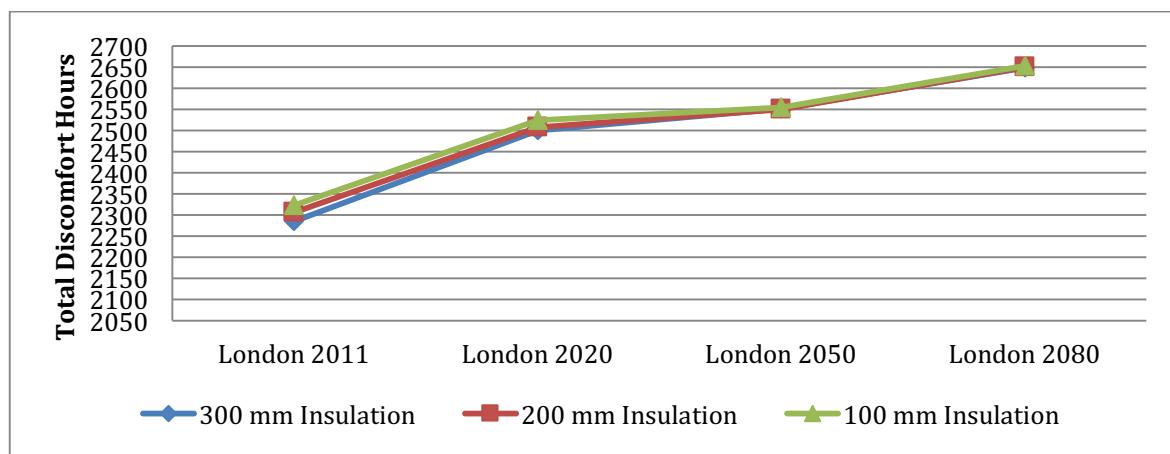


Figure 3. Comparison of insulation thickness effect in BB construction, London

Figure 3 suggests that for the brick and block BB wall, reducing the insulation thickness (from that which gave a 0.1 U-Value) to 200mm and 100 mm (U-Values of 0.13 and 0.2 respectively) does not give significant differences in annual discomfort hours. For the ICF wall (Figure 4), the maximum insulation thickness (320mm) for the 0.1 U-Value provides a small comfort advantage for current weather data compared to the 200mm (0.15 U-Value) and 100mm (0.28 U-Value) insulation thicknesses. However, this benefit narrows and then disappears during the following decades.

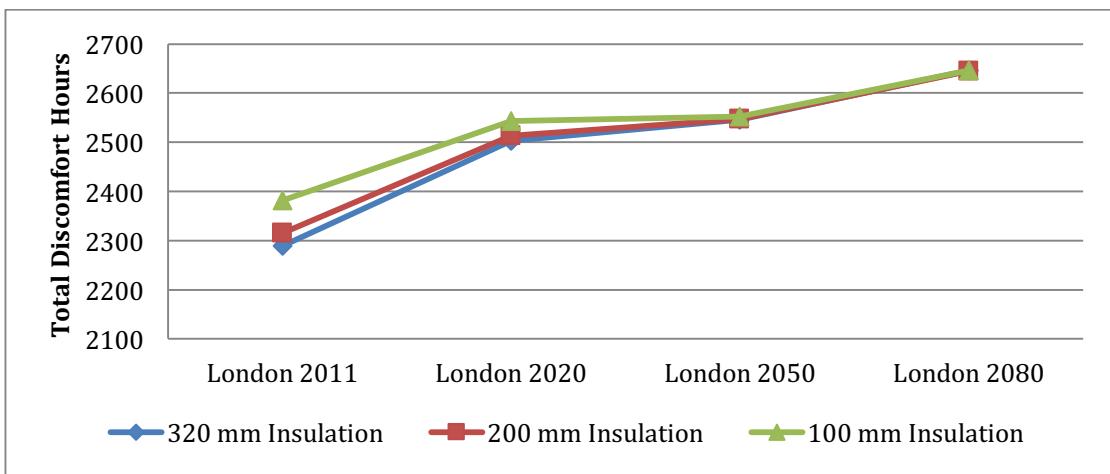


Figure 4. Comparison of insulation thickness effect in ICF construction, London

The TF wall (Figure 5) demonstrates a similar trend to the ICF wall, with an initial small comfort benefit for London 2011 weather data as the insulation thicknesses are reduced (U-Values of 0.15 and 0.24 W/m<sup>2</sup> K for 200 and 100 mm thicknesses respectively). However, as with the ICF wall, the benefit is soon lost.

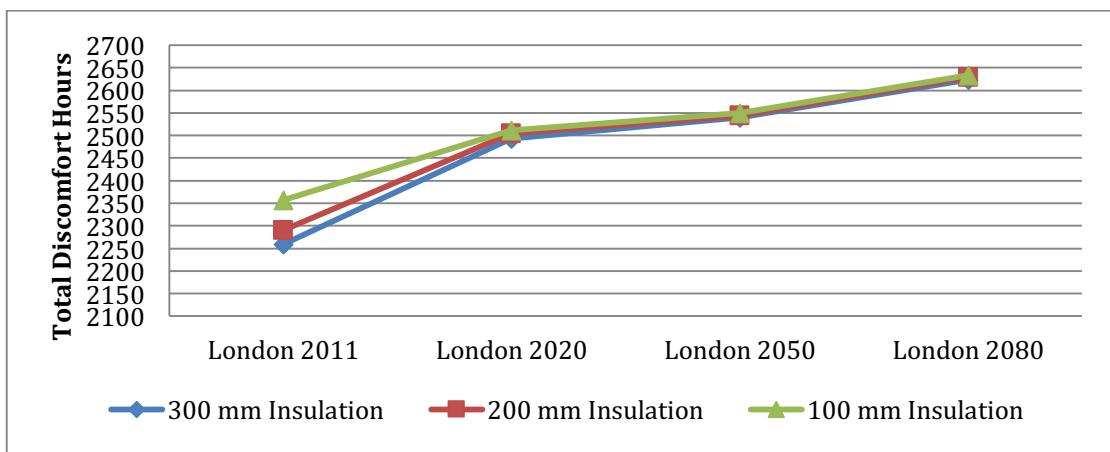


Figure 5. Comparison of insulation thickness effect in TF construction, London

For the SF and SIP systems (Figures 6 and 7), a 100mm decrease in insulation (0.1 and 0.14 U-Values respectively) has a negligible effect on total discomfort hours for any period.

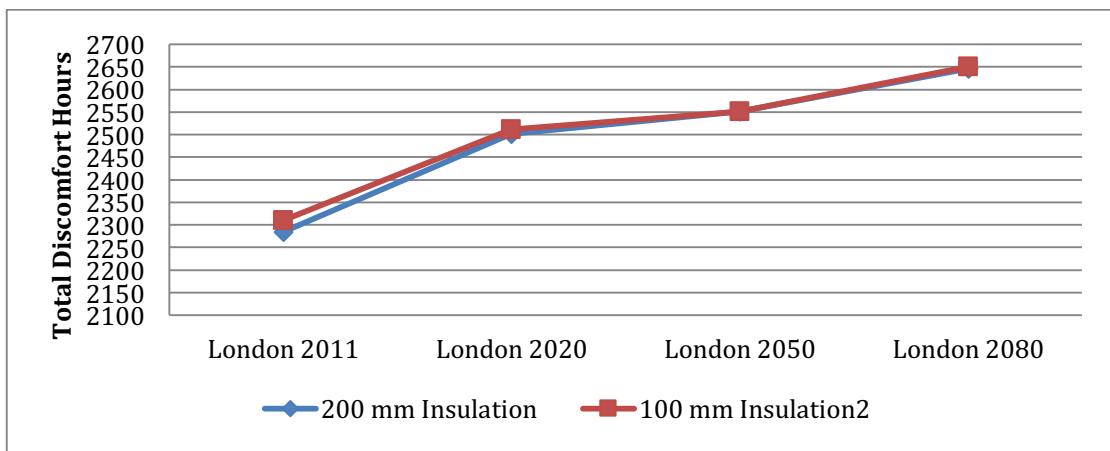


Figure 6. Comparison of insulation thickness effect in SF construction, London

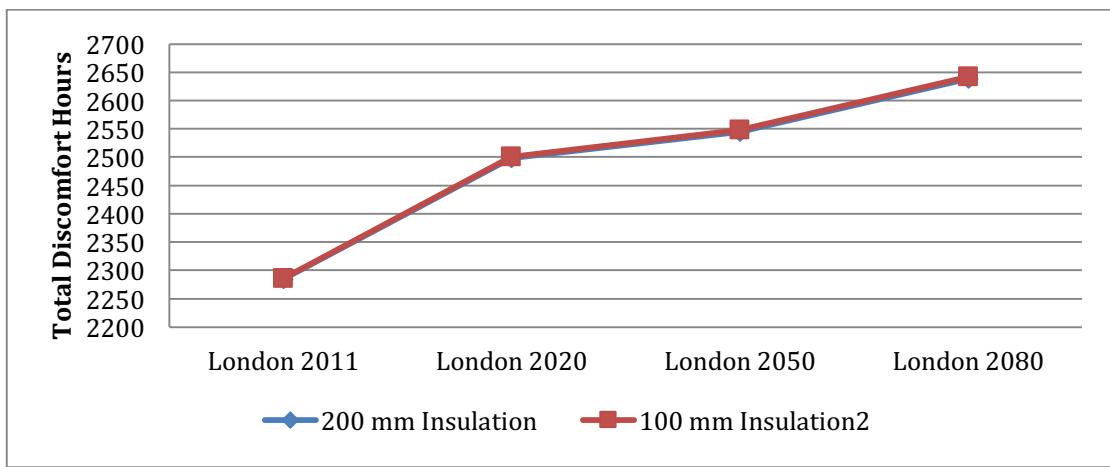


Figure 7. Comparison of insulation thickness effect in SIP construction, London

In general, it seems that any changes in insulation thickness that increases U-Values up to about 0.3 W/m<sup>2</sup>K will not impact on total annual discomfort hours. It should be mentioned that reducing insulation thickness is likely to decrease the overheating risk and increase the overcooling risk for UK summers and winters respectively. However, this study has considered only the total annual hours of discomfort, adding together both cold and hot discomfort hours to find the annual total.

This point is illustrated in Figure 8. The y-axis shows the number of hours during a year that a certain temperature was experienced in the room for the ICF wall with two insulation thicknesses. So, the ICF room with 100mm insulation experienced 100 hours at 11°C temperature while the 300mm ICF wall had nearly zero hours at 11°C. Even though the overall discomfort hours over a year are close for both ICF constructions, the distributions of the hours in each temperature band are not similar.

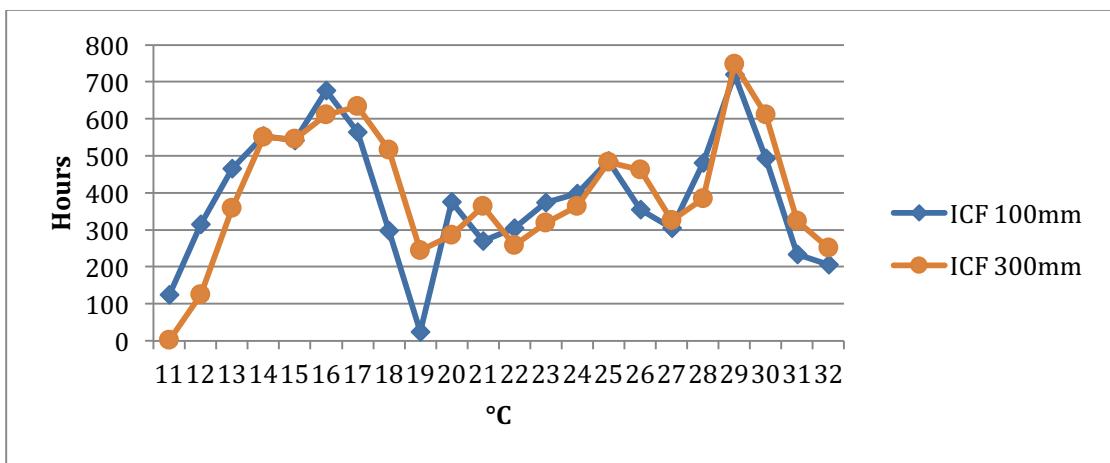


Figure 8. Hours at each temperature band interval for an ICF wall with 100 and 300mm of insulation

## Conclusion

This study has examined the effects of construction type, thermal mass and thermal insulation on annual thermal discomfort hours for different climate periods in London. The results for a simple house form suggest that the annual discomfort hours are relatively insensitive to the type of building system used. The number of discomfort hours increase in a warming future, but with little difference in total discomfort hours between the differently constructed spaces. Timber frame shows a slightly better performance compared to the

others, but no one “correct” construction can be recommended to decision-makers. This finding agrees with a comfort study by the Three Regions Climate Change Group (TRCCG, 2008) of 1960s houses and flats in London, East and Southeast of England. The Group concluded that ventilation strategies, solar control and cooler floors were more effective approaches to improving comfort in UK housing compared to increasing insulation levels.

It appears that a preferred building materials/details can be chosen without worrying that it might be a risky choice for future discomfort. However, there is the caveat that looking at total annual values of discomfort hours can obscure the balance between the ‘hot’ and ‘cold’ discomfort hours. More research is needed to disaggregate the hourly types of discomfort as the energy used to meet a heating demand per °C can be provided much more efficiently and economically than the energy needed to meet the same per °C cooling demand.

## References

- AECB. (2017, February 27). CarbonLite. Retrieved from <http://www.carbonlite.org.uk/carbonlite/passivhaus.ph>
- ASHRAE. (2004). Thermal Environment Conditions for Human Occupancy. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers organization.
- CIBSE. (2006). Guide A: Environmental Design. London: Chartered Institution of Building Services Engineers.
- Gupta, R., & Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. *Building and Environment*, 8-17.
- Humphreys MA. (1976). Comfortable indoor temperatures related to the outdoor air temperature. *Building Services Engineer*, 44, 5-27.
- Lisq, K. (2006). Integrated approach to risk management of future climate change impacts. *Building research and information*, 1-10.
- MacLaren, F., Dennis, L., & Mourshed, M. (2012). Public opinions on alternative lower carbon wall construction techniques for UK housing. *Habitat International*, 3-5.
- Orme, M., Palmer, J., & Irving, S. (2003). Control of overheating in well-insulated housing. In: *Building sustainability: value and profit*. Retrieved Mar 7, 2012, from <http://www.cibse.org/pdfs/7borne.pdf>
- SERG (2016). Sustainable Energy Research Group, University of Southampton), CCWeatherGen: Climate Change Weather File Generator for the UK. Retrieved from <http://www.serg.soton.ac.uk/ccweathergen> Retrieved Mar 1, 2017
- Tabatabaei Sameni, S., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 222-235.
- TRCCG (2008) Your home in a changing climate: retrofitting existing homes for climate change impacts. ARUP, London.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Adapting to a Warmer Climate – Affordable Low-carbon Retrofits and Occupant Options for Typical Australian Houses

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**Abstract:** This paper describes the cost-effectiveness of adapting Australian houses and occupant behaviour to reduce room temperatures and heating and cooling requirements in a warming world. We used CSIRO's Australian Climate Futures framework and Belcher's "morphing" technique to project the 2050 climate; a novel Standard Effective Temperature (SET\*) thermal comfort approach where occupants modify their behaviour and tolerate higher temperatures; a do-it-yourself (DIY) retrofit approach to find the most cost-effective retrofits simulated for typical Australian houses; and combinations of retrofits with small, medium and large simple payback periods (SPPs) to suit occupant categories. The most effective strategies were modifying occupant behaviour; partitions to reduce the conditioned volume; ceiling and roof insulation; gap sealing; and retrofits to suit the type of house construction (such as wall and under-floor insulation, and internal brick walls for added thermal mass if there was a concrete floor). The research suggests that deeper retrofits may be needed than those provided by the large SPP retrofit combinations in 2050 to adapt to high indoor temperatures, even after changing behaviour regarding higher air speeds and lighter clothing.

**Keywords:** cost-effective retrofits, existing houses, carbon emissions, extreme climate change, occupant adaptation

### Introduction

Adapting a household for climate change means changing occupant behaviour or retrofitting the house for the projected effects of regional climate changes that may occur over the remaining life of the house (e.g. for higher house temperatures, greater wind speeds or bigger floods).

Global temperatures are rising at a potentially catastrophic rate (Nuccitelli 2016). The number of storms, floods and temperature-related natural disasters have increased from 300 to 900 over the past 35 years, with many hundreds of billions of dollars in property damage since 1980 alone (MunichRe et al., 2015, pp. 43–44). Sir Nicholas Stern has now stated that he had greatly underestimated the damages from climate change, following the poor response of global leaders (ClimateWire and Narayanan, 2013).

Australia has agreed to keep global temperature increases well below 2 °C, implying a zero-emissions economy by 2050, but has one of the world's worst-performing building stocks per capita, and where residential buildings are responsible for around 13% of all Australia's emissions. Since around 30% of the 2050 residential stock exists now and houses

make up 80% of residences, it is important to retrofit existing houses for climate change (Shiel, 2017).

Improving the performance of the envelope in the housing industry is difficult due to the number of stakeholders, low energy efficiency of older houses, and a lack of relevant knowledge, of both owners and building contractors.

Since improvements are more likely if convenient, easy and affordable (Bond et al., 2011), the aim of this paper is to find cost-effective low-carbon retrofits and behaviour-change strategies to lower the effective temperatures felt by household occupants. These adaptation strategies may also mitigate climate change by lowering energy use and therefore carbon emissions.

## **Methodology**

### ***Climate Change***

We undertook climate change modelling with the Climate Futures tool (CSIRO, 2016) to find the most appropriate general climate model (GCM) based on 1) the representativeness of the ‘Maximum Consensus’ case, 2) model skill and 3) availability of requisite variables (Clarke et al., 2011; J. J. Shiel et al., 2017).

Although two scenarios were examined for 2050, only one is reported here, namely the Extreme Climate Change scenario. (The Scarce Resource scenario results are reported in (J. Shiel et al., 2017)). The Extreme Climate Change scenario is a future of “business as usual” (Peters et al., 2013, p. 5) with a plentiful supply of fossil fuels, and corresponds with RCP8.5, where RCP is a Representative Concentration Pathway (RCP) (van Vuuren et al., 2011).

We generated plausible Reference Meteorological Year (RMY) Adelaide climate data for 2050 (Shiel, 2017) using:

- Belcher’s “morphing” technique (Belcher et al., 2005) with the selected GCM, and
- the Adelaide 1990 RMY climate file dataset from NatHERS.

### ***Retrofits***

The characteristics of the existing houses modelled are provided in Table 1, and these were chosen to match typical Australian house constructions e.g. with external walls of weatherboard, cavity brick, and brick veneer (DEWHA, 2008; Shiel, 2017).

Table 1 – House Characteristics for the three existing houses H1 – H3

	<b>House 1</b>	<b>House 2</b>	<b>House 3</b>
<b>Era</b>	1950s	1980s	2010s
<b>Area</b>	112m <sup>2</sup>	187m <sup>2</sup>	223m <sup>2</sup>
<b>Ext. Walls</b>	Weatherboard	Cavity brick	Brick veneer
<b>Int. Walls</b>	Plasterboard	Single Brick	Plasterboard
<b>Floor</b>	Timber floor	Timber floor	Concrete slab
<b>Garage</b>	None	Single car	Double car
<b>Ceiling insulation</b>	None	None	R1 K·m <sup>2</sup> /W
<b>Roof</b>	Tile	Tile	Metal
<b>Ceiling Height</b>	2.74m	2.4m	2.4m
<b>Eaves</b>	450mm	600mm	600mm
<b>Windows</b>	Timber single-glazed windows	Aluminium single-glazed windows	Aluminium single-glazed windows

Seventy retrofits were modelled for each house including partial air-conditioning; perimeter insulation; weather-stripping; adding thermal mass; and other measures such as low-e window films and external vegetation.

We used the NatHERS AccuRate software to calculate the required energy for comfort for the retrofits; estimated their do-it-yourself (DIY) cost and carbon savings for a split-system air-conditioner in Adelaide; and ranked the retrofits by simple payback period (SPP). Retrofits were combined for three sets of costs that had small, medium and large payback periods to suit occupant categories of tenants; of owners and landlords; and of householders who would like to carry out deep retrofits (J. Shiel et al., 2017).

### ***Occupant Behaviour Changes***

For occupant behaviour change, we rely on a previous study (J. J. Shiel et al., 2017) of the effects on energy savings of an alternative Standard Effective Temperature (SET\*) comfort approach, for the same warming climate scenarios for 2050. It suggested that dwelling occupants could be comfortable at higher temperatures by changing their behaviour regarding air speed and clothing.

The effective temperature felt by occupants with this alternative SET\* approach depends on the six parameters: air temperature, radiant temperature, air speed, humidity, clothing and metabolic rate, with a wider comfort temperature band than used in NatHERS.

## **Results**

The results reported here are for the Adelaide region (“Southern & SW Flatlands (East)”) Extreme Climate Change scenario in 2050, with an air-conditioner and DIY costings.

### ***Climate Change***

HADGEM2-ES was found to be the most appropriate GCM and the annual average of the mean monthly increase for temperature was projected to be 1.8 K from 1995 to 2050 (CSIRO, 2016; J. Shiel et al., 2017).

### ***House Retrofits***

Figure 1 shows the single retrofit carbon savings by payback period for House 2, which shares characteristics of House 1 (e.g. a timber floor) and House 3 (a garage with concrete floor) and illustrates the general trend of single retrofits. It has a table that ranks the House 2 cost-effective retrofits by payback period, and similar retrofits are colour-coded as shown in Table 2. Furthermore, the size of carbon savings provide a general indication of how effective each retrofit is in keeping the temperatures of all the conditioned rooms in the NatHERS temperature comfort band.

Table 2 shows the indicative costs and carbon savings of cost-effective single retrofits for House 3, and includes only the retrofits for Houses 1 and 2 where they are in common. The older House 1 has more cost-effective retrofits than Houses 2 and 3 (Shiel, 2017).

Figure 2 shows the carbon savings and SPPs for various combinations of retrofits for each house to suit occupant categories. The retrofits that make up the large SPP combination for each house are provided in Table 3, and the small and medium SPP retrofit combinations are mostly subsets of these sets of retrofits (Shiel, 2017).

## Adapting to Indoor 2050 Temperatures

Figure 3 shows the effects of the large SPP set of retrofits on the free running, or naturally conditioned temperatures of houses 1 and 3, for the living room and bedroom one, on the hottest day in 2050.

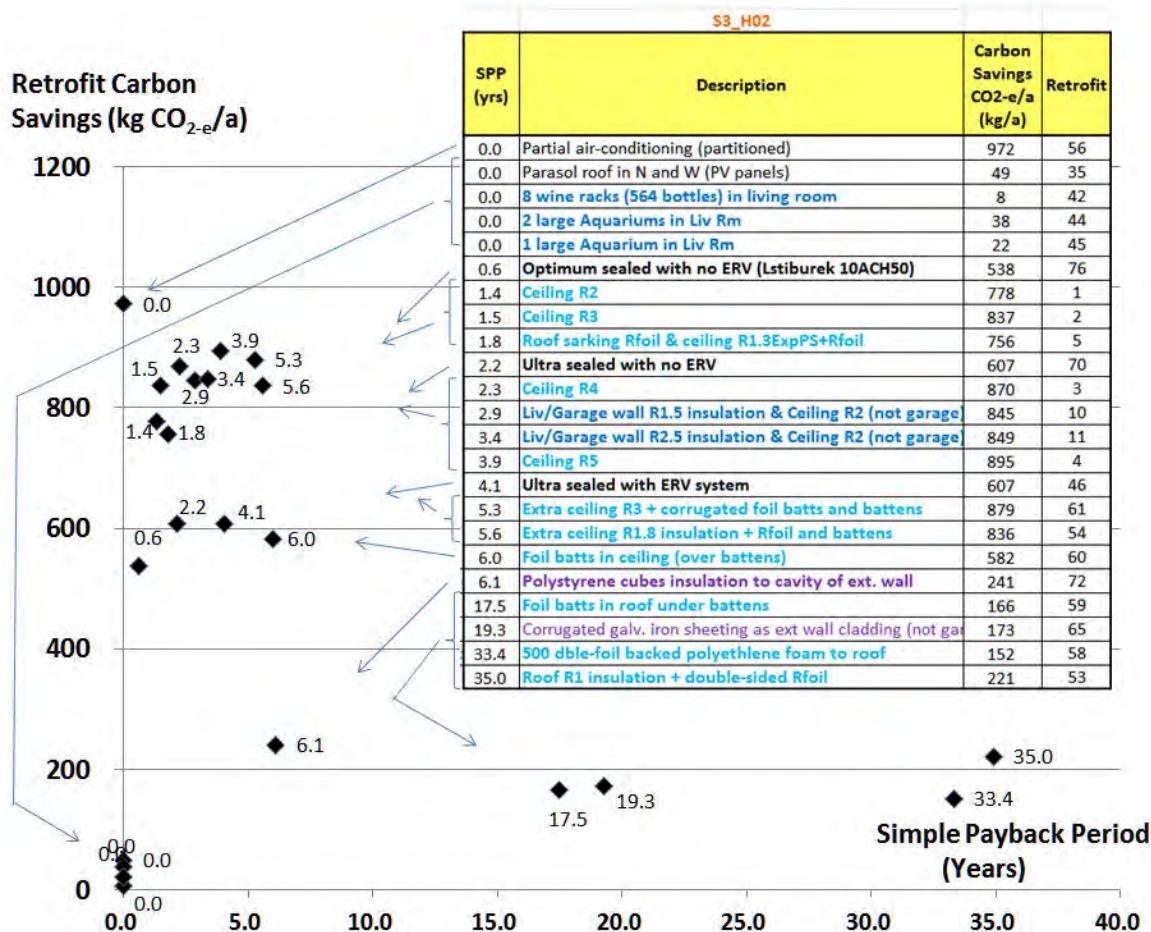


Figure 1 - The carbon savings by payback period of cost-effective do-it-yourself (DIY) retrofits for House 2, a 1980s cavity brick and timber floor house. The values are labelled with their SPPs, and the table is ranked by SPP and colour-coded as in Table 2. The other house results are in (Shiel, 2017).

## Behaviour Change

The SET\* comfort approach provided an extended comfort temperature band for free-running thermostat values in Adelaide of 14.2 °C to 34.8 °C based on modified air speed and clothing levels where the occupants would effectively feel like it was 16 °C to 28 °C (J. J. Shiel et al., 2017).

## Discussion

Before adapting a house for climate change, a life-cycle household carbon and costing analysis should be carried out, especially with housing shortages in Australia (Iyer-Raniga, 2010).

## Single Retrofits

The most cost-effective retrofits to lower Australian house temperatures are partitions to reduce the conditioned volume, ceiling and roof insulation, optimum weather-stripping e.g. by Lstiburek in (Aynsley and Shiel, 2017), and those that suit the type of house, e.g.

- wall insulation for the weatherboard and cavity wall houses with timber floors;
- under-floor insulation for the old weatherboard house; and
- added thermal mass with internal walls where there is a concrete floor.

Some retrofits with little effect were included because of the DIY costing approach, where they were assumed to be at zero cost, e.g. if part of a hobby or already part of the house such as aquariums or photovoltaic panels (Shiel, 2017).

Table 2 –Cost-effective single retrofits of House 3 and where these are shared with Houses 1 and 2. The retrofits are colour coded for roof and ceiling (light blue), walls (purple), floors (brown), thermal mass (dark blue), sealing (bolded black) and other (black).

<b>Retrofit</b>	<b>Description</b>	<b>House 3</b>		<b>House 2</b>		<b>House 1</b>	
		<b>SPP (yrs)</b>	<b>Carbon Savings CO<sub>2</sub>-e/a (kg/a)</b>	<b>SPP (yrs)</b>	<b>Carbon Savings CO<sub>2</sub>-e/a (kg/a)</b>	<b>SPP (yrs)</b>	<b>Carbon Savings CO<sub>2</sub>-e/a (kg/a)</b>
35	Parasol roof in N and W (PV panels)	0.0	34	0.0	49	0.0	59
44	<b>2 large Aquariums in Liv Rm</b>	0.0	35	0.0	38	0.0	22
45	<b>1 large Aquarium in Liv Rm</b>	0.0	22	0.0	22	0.0	16
42	<b>8 wine racks (564 bottles) in living room</b>	0.0	10	0.0	8	0.0	74
76	<b>Optimum sealed with no ERV (Lstiburek 10ACH50)</b>	1.2	365	0.6	538	0.9	379
3	<b>Ceiling R4</b>	6.0	254	2.3	870	1.4	890
10	<b>Liv/Garage wall R1.5 insulation &amp; Ceiling R2 (not garage)</b>	10.6	190	2.9	845		
59	<b>Foil batts in roof under battens</b>	49.8	66	17.5	166	4.4	364
65	<b>Corrugated galv. iron sheeting as ext. wall cladding (not garage)</b>	19.8	80	19.3	173	6.9	263
74	<b>Polystyrene cubes insulation to full 140mm cavity of ext. wall</b>	16.9	126				

### **Importance of Thermal Mass**

An envelope with low diffusivity (where diffusivity is conductivity divided by thermal mass) is needed to maintain comfortable free running internal temperatures in temperate climates (Barrios et al., 2011). So having the appropriate level of thermal mass is an important retrofit to keep future energy requirements low, in addition to the right levels of radiation and insulation (Baggs and Mortensen, 2006).

Thermal mass retrofits were cost-effective for the two houses with attached concrete floor garages by adding an insulated internal garage brick wall. The brick wall retrofit was included as DIY because some householders can undertake this retrofit and it was an important retrofit while contractor costs were included for a few other retrofits, such as the ERV system (Shiel, 2017).

### **Combined Retrofits**

For retrofit combinations, the partial air-conditioning retrofit was not used, since it does not have a temperature-lowering adaptation effect, but can be useful in lowering emissions.

Retrofit combinations with a small payback period of three years may suit tenants, those with little disposable income, those who may not be staying long in the house, or those in old houses that will only experience mild effects of climate change. Those with a

higher level of disposable income could carry out the medium level of SPP retrofit combinations, whereas households keen to carry out deep retrofits could use the retrofit combination with a large SPP.

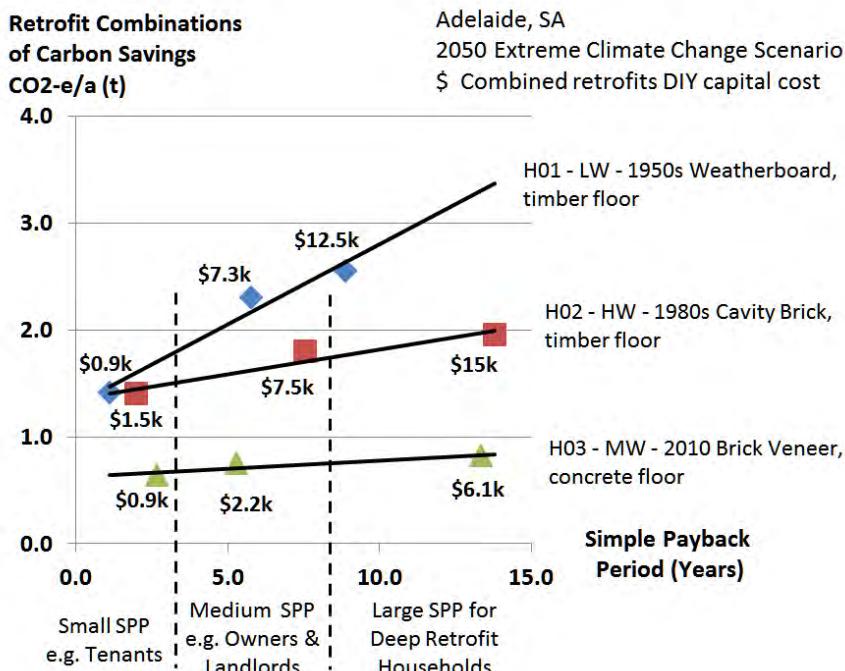


Figure 2 - Carbon savings by SPP for combinations of retrofit by house type and era (with 1950s weatherboard or light-weight walls – LW; 1980s cavity brick or heavy-weight walls – HW; and 2010 brick veneer or medium-weight walls – MW) with degree of retrofit (small, medium and large) to suit occupant categories. The dollar label refers to the DIY capital cost of the retrofit SPP combination.

### **Adapting Houses and Occupant Behaviour for 2050**

Figure 3 indicates that the living room free running temperatures after the large retrofit combinations in Table 3 will reach 43 °C for House 1 and 41 °C for House 3, a reduction of up to 7 K and 6 K respectively.

Table 3 – The retrofits making up the combinations of the large payback periods, to suit deeper retrofit households as shown in Figure 2 (retrofits are bolded if in common).

House 1	House 2	House 3
<b>3 - Ceiling R4 Insulation;</b> 16 - Underfloor 90mm gap & 1500 bubble Insulation with dbl-sided Rfoil; 26 - 5m high deciduous trees to North windows; 32 - Low-e film applied to windows; <b>35 - Parasol roof in N &amp; W roof;</b> <b>42 - 8 wine racks (564 bottles);</b> <b>44 &amp; 45 - 3 large Aquariums;</b> 49 - 1.4m dia Ceiling fans; 53 - Roof R1 insulation; 55 - Green ivy on North & West walls; <b>59 - Foil batts in roof under battens;</b> 62 - Foil batts stapled under floor; 67 - Carpet to timber floor; <b>72 - Polystyrene cubes insulation to cavity of ext. wall;</b> 76 - Optimum sealing (Lstiburek 10ACH <sub>50</sub> ).	5 - Roof sarking Rfoil & ceiling R1.3 expanded polystyrene + Rfoil; <b>10 - Add Liv/Garage brick wall with R1.5;</b> 18 - R2.5 polystyrene batts under timber floor; 34 - Low-e film tint to non-North windows; <b>35; 42; 44 &amp; 45; 59;</b> 58 - 500 dbl-foil backed polyethylene foam to roof; 60 - Foil batts in ceiling; 62 - Foil batts underfloor; <b>65 - Corrugated galv. iron sheeting as ext. wall cladding;</b> 72; 76.	3; 10; 35; 42; 44 & 45; 59; 65; 74 - Polystyrene cubes to full 140mm cavity of ext. wall; <b>76</b>

In Figure 3, for bedroom one in House 3, the maximum night temperature after retrofits is 34 °C, lowering the maximum temperature by 2 K. However, for House 1 the bedroom one temperatures are actually higher after the retrofits, due to the bedroom's location on the western side and the retrofits preventing heat escaping at night (e.g. perimeter insulation and greater sealing).

Household occupants can adapt with behaviours such as using higher air speeds and wearing lighter clothing to tolerate 34.8 °C during the day and 30.4 °C at night to feel like it is 28 °C and 26 °C respectively, with night comfort under high temperatures deserving more research (J. J. Shiel et al., 2017). However, when temperatures exceed 35 °C, there is a high risk of heat stroke as heat exchange with the environment is greatly diminished (Hanna and Tait, 2015, p. 8050), particularly for infants and elderly.



Figure 3 – The change in living and bed room free running temperatures after the combined retrofits of the largest payback period for the hottest day in 2050. These are for House 01 (1950s weatherboard) and House 03 (2010 brick-veneer), where the external maximum temperatures for day and night were 46 °C and 36 °C respectively, with maximum corresponding relative humidity levels of 20% and 38% respectively.

### Cool Retreats

These results suggest that deeper retrofits are required to lower temperatures, and that there should be a greater focus on retrofitting rooms to become cool retreats. This includes changing room types and ventilation strategies e.g. moving bedrooms away from the western side, having separate living spaces for winter and summer, as well as specific retrofits and technologies to keep one room cooler (Aynsley and Shiel, 2017; Roaf et al., 2005; Saman et al., 2013).

### Conclusion

The key findings are that:

- Many cost-effective retrofits can be found for older timber-floored Australian houses to adapt to a warmer future, with a fewer number identified for more modern houses with concrete floors.
- Retrofit combinations for small, medium and large payback periods were found to suit different occupant categories, with up to a 7 K reduction in room temperatures in 2050.
- Large payback period retrofit combinations as well as occupancy behaviour change may still be insufficient for Adelaide in 2050 for the Extreme Climate Change scenario, requiring deeper retrofits and special room modifications as cool retreats.

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## References

- Aynsley, R., Shiel, J., 2017. Ventilation Strategies for a Warming World. *Archit. Sci. Rev.* 60, 249–254. doi:10.1080/00038628.2017.1300764
- Baggs, D.W., Mortensen, N., 2006. Thermal Mass in Building Design (No. EDG4), Environment Design Guide. The Royal Australian Institute of Architects (RAIA), Melbourne Victoria.
- Barrios, G., Huelsz, G., Rechtman, R., Rojas, J., 2011. Wall/roof thermal performance differences between air-conditioned and non air-conditioned rooms. *Energy Build.* 43, 219–223. doi:10.1016/j.enbuild.2010.09.015
- Belcher, S., Hacker, J., Powell, D., 2005. Constructing design weather data for future climates. *Build. Serv. Eng. Res. Technol.* 26, 49–61.
- Bond, S., Pacifici, C., Newman, P., 2011. Sustainability in Housing: Perceptions of Real Estate Agents, Building Professionals & Householders.
- Clarke, J., Whetton, P., Hennessy, K., 2011. Providing application-specific climate projections datasets: CSIROs climate futures framework, in: Proceedings of MODSIM, International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand. Presented at the MODSIM2011, 19th Int. Congress on Modelling and Simulation, Perth, WA, Australia, pp. 12–16.
- ClimateWire, Narayanan, N., 2013. Climate Change Worse Than Expected, Argues Lord Stern. *Sci. Am.* <https://www.scientificamerican.com/article/climate-change-worse-than-expected-argues-lord-stern/> (Accessed: 20 February 2017).
- CSIRO, 2016. Australian Climate Futures: Detailed Projections [WWW Document]. URL <https://www.climatechangeaustralia.gov.au/en/climate-projections/climate-futures-tool/detailed-projections/> (accessed 11.1.16).
- DEWHA, 2008. Energy Use in the Australian Residential Sector 1986-2020. Department of the Environment, Water, Heritage and the Arts, Australia.
- Hanna, E.G., Tait, P.W., 2015. Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. *Int. J. Environ. Res. Public. Health* 12, 8034–8074.
- Iyer-Raniga, U., 2010. Detonate or Renovate? The Life Cycle Perspective.
- MunichRe, Cooper, S., Hedde, C., Rauch, E., Hartwig, R., 2015. NAT CATS 2014: What's going on with the weather?
- Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M.R., Wilson, C., 2013. The challenge to keep global warming below 2 °C. *Nat. Clim. Change* 3, 4–6. doi:10.1038/nclimate1783
- Roaf, S., Crichton, D., Nicol, F., 2005. Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide. Architectural Press, Amsterdam.
- Saman, W., NCCARF, UniSA, 2013. A framework for adaptation of Australian households to heat waves. National Climate Change Adaptation Research Facility (Australia), Gold Coast, Qld.
- Shiel, J., Moghtaderi, B., Aynsley, R., Page, A., Clarke, J., 2017. Rapid Decarbonisation of Australian Housing in Warm Temperate Climatic Regions for 2050 - (to be confirmed for future publication), in: Proc. of World Renewable Energy Congress XVI. Presented at the World Renewable Energy Congress XVI, Perth, WA, Australia.
- Shiel, J.J., 2017. Low-carbon and affordable retrofits of Australian housing for climate change and scarce resource scenarios (PhD dissertation - forthcoming). University of Newcastle, Newcastle, NSW, Australia.
- Shiel, J.J., Aynsley, R., Moghtaderi, B., Page, A., 2017. The importance of air movement in warmer temperatures: a novel SET\* house case study. *Archit. Sci. Rev.* 60, 225–238. doi:10.1080/00038628.2017.1300763
- van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. *Clim. Change* 109, 5–31. doi:10.1007/s10584-011-0148-z



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Simulation of microclimatic effects for green infrastructure in the city of São Paulo, Brazil

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**Abstract:** Starting from previous studies concerning the impact of vegetation in urban microclimate (effects on air temperature, mean radiant temperature, surface temperature, humidity, wind speed and direction) for the city of São Paulo, Brazil, this study aims to achieve: (1) a 3D parametrization of Brazilian trees using the module Albero on ENVI-met model V4, considering local leaf density and canopy structure collected during fieldworks; (2) the calibration of the model based on field measurements carried out locally on urban parks; (3) the simulation of different green distribution scenarios. The method includes field measurements of air temperature, humidity, globe and surface temperature, as well as registering other data that characterizes local microclimatic conditions (wind speed and direction, global solar radiation, sky view factor), and the comparison between measured and simulated data on ENVI-met V4. After that, a base case and other parametric scenarios were proposed to incorporate different greening strategies inside dense urban blocks. According to the simulation results, for different tree canopy characteristics, a maximum reduction of up to 1,6K in air temperature and 13,6K for surface temperature were found, when comparing the base case to the street trees scenarios, indicating a more homogeneous distribution of the vegetation effect on microclimate.

**Keywords:** urban vegetation, urban microclimate, ENVI-met, leaf density

### Introduction

The process of urbanization has changed the relationship between society and the natural environment. The direct consequence of this process is the change in the characteristics of urban surfaces (Stone, 2012). Thus, urbanization results in changes in physical properties of surfaces, including water content, thermal capacity, conductivity, albedo and emissivity, causing a reduction in evaporation rates (Voogt and Oke, 2003).

The lack of vegetation influences the increase of the air temperature due to the heating of the surfaces (floors, facades and roofs) throughout the day and the reduction of evaporative surfaces that perform heat exchange. In addition, other factors also contribute to this effect: change in the geometry of the urban fabric (height and width ratio of the canyon), use of materials that store part of the sensible heat due to its thermal properties and emission of anthropogenic heat generated by burning fossil fuel (Oke, 1978).

According to Stone (2012), three main strategies need to be considered to mitigate warming in large urban areas: (1) planting trees and planning new configurations using vegetation (green roofs, green walls, sky gardens); (2) increasing the albedo, incorporating

techniques to reduce the heating of the roofs or replacing surfaces coatings with more reflective materials; (3) implementing of energy efficiency programs committed to reduce greenhouse gas emissions.

At the microscale, trees have been shown to be particularly beneficial in lowering urban temperatures and improving human thermal comfort due to both evapotranspiration and shading. Important determinants of the intensity of cooling from vegetation include tree location, size and canopy coverage, planting density and irrigation management and as much as 80% of the cooling effect of trees is from shading (Coutts *et al.*, 2013).

Starting from previous studies concerning the impact of vegetation in urban microclimate (effects on air temperature, mean radiant temperature, surface temperature, humidity, wind speed and direction) for the city of São Paulo, Brazil, this study adopted the model ENVI-met, that considers the density of leaves to simulate the micro scale interactions of surface-vegetation- atmosphere. With the new advancements on ENVI-met, trees are represented by clusters of LAD cells, forming a bigger entity with a three-dimensional geometry (3D-plants) and are managed by a special editor program called Albero (Simon, 2016).

This study aims to achieve: (1) a 3D parametrization of Brazilian trees using the module Albero on ENVI-met model V4, considering local leaf density and canopy structure collected during fieldworks; (2) the calibration of the model based on field measurements carried out locally on urban parks; (3) the simulation of different green distribution scenarios, analysing the outcomes of microclimate variables.

## **Method**

The method includes field measurements of air temperature, humidity, globe and surface temperature, as well as registering other data that characterizes local microclimatic conditions (wind speed and direction, global solar radiation, sky view factor) and the comparison between measured and simulated data on ENVI-met V4. After that, a base case and other parametric scenarios were proposed to incorporate different greening strategies inside dense urban blocks.

On-site measurements were carried out to monitor representative local hot weather conditions. Subsequently, by the results of the local microclimatic data and vegetation characteristics, computer simulations calibrated ENVI-met V4, based on the comparison of measured and simulated data, with a more detailed 3D modelling studies that considers the existing vegetation at an urban park.

After simulation results, analyses were carried out to indicate a better use and distribution of vegetation as a strategy to mitigate urban warming in a subtropical changing climate.

## **Area of Study**

The city of São Paulo is located in Southeast of Brazil (23°32'S, 46°37'W). According to IBGE (2015), the population is almost 21 million inhabitants in the metropolitan area, distributed in an overall area of 8051km<sup>2</sup>, where 2200 km<sup>2</sup> of the Municipality is an urbanized area in which 65% of population lives today.

São Paulo has a humid subtropical climate with mild and dry weather conditions during winter. Summer is moderately warm with average temperatures varying between 19°C and 28°C, and annual rain varies between 1250 to 2000mm (IBGE, 2015).

This work was carried out testing a greenery increase in the surrounding blocks of Tenente Siqueira Campos Park (Trianon Park), which is located at Paulista Avenue, considered an important axis for cultural and financial activities in the city center. This area, according to data from the Municipal Environmental Agency (SVMA, 2011), is part of the Subprefecture of Sé, with an average rate of  $6,18\text{m}^2$  of green area per inhabitant, contrasting with other nearby neighborhoods such as Pinheiros subregion, with  $22.5 \text{ m}^2$  of green area per inhabitant.

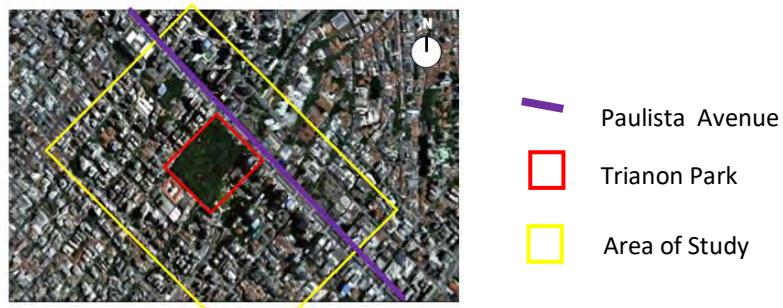


Figure 1. Area of study surrounding Trianon Park

### **Field Measurements**

Climate monitoring was carried out for four consecutive days, during the period from April 2<sup>nd</sup> to 5<sup>th</sup> 2016. In the Bela Vista borough, along Paulista Avenue, two areas were chosen for the measurements: one inside Trianon Park (P1) and another one in the courtyard of an office building (P2). In the point 1, a meteorological station was placed over open soil covered with small plants and under high dense trees. In the point 2, the meteorological station was placed over a concrete pavement with gravel and located in a dense building block without vegetation (Figure 2).

One of the purposes of the measurements was to compare microclimatic data (air temperature, humidity, solar radiation, surface temperature, wind speed and direction) registered in a dense urban park area surrounded by high-rise buildings without vegetation. These data were essential for the calibration process in ENVI-met model.

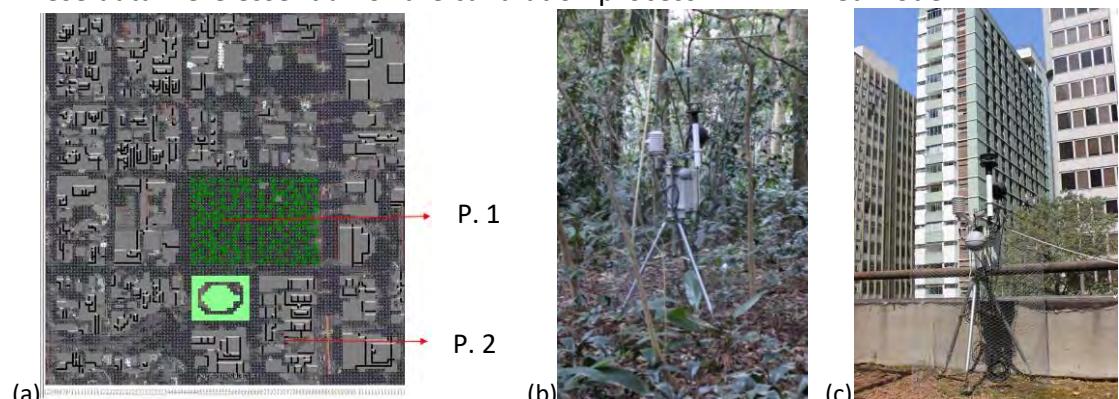


Figure 2. (a) Location of two points for microclimatic measurements; (b) Meteorological station at Trianon Park (Point 1); (c) Meteorological station at Paulista courtyard (Point 2).

### **ENVI-met V.4 model simulations**

The ENVI-met is a three-dimensional model to simulate the interactions between surface-vegetation-atmosphere for urban environments with resolutions of 0.5m to 10m in space and up to 10 seconds in time. In this way, it allows analysing, in a micro-scale perspective, the

interactions between the urban design and the microclimate (Bruse and Fleer, 1998; Huttner, 2012; Simon, 2016).

This prognostic model is based on the laws of fluid dynamics and thermodynamics. Includes simulations for: airflow around and between buildings; process of heat and water vapour exchange on the surface of the floor and facades; local turbulence and its dissipation rate; parameters of heat exchange with vegetation; dispersion of pollutant particles; and biometeorological parameters such as the predicted mean vote (PMV) and physiological equivalent temperature (PET).

In order to evaluate the microclimate benefits of vegetation, a numerical model was implemented to calculate the main factors related to vegetation: transpiration, evaporation, sensible heat flux, turbulent heat and steam fluxes; stomata resistance, leaf energy balance and water balance of the soil-vegetation system. It considers not only the shading effect of the trees, but also the physiological process of plants, based on the A-gs model (Jacobs, 1994) to calculate stomata conductance (Bruse, 2004).

In ENVI-met V4, besides the 1D plants database, a toolbox called Albero was also implemented with a more sophisticated way to define the new 3D plant geometries. It offers data management, plant generation and modification and it is directly integrated into the new ENVI-met database system (Bruse, 2017). For this study, Albero was used to edit and create new trees that could approximate to the characteristics of the existing trees in São Paulo.

### ***Parametrization of tropical trees with Albero***

This model considers the parameter Leaf Area Density – LAD<sup>1</sup> to calculate plants' physiology. According to the ENVI-met 3D plants database, there are 14 types of vegetation, which have specific characteristics according to the following aspects: CO<sub>2</sub> fixation type (C<sub>3</sub> or C<sub>4</sub> plants), leaf type, short-wave albedo, height of the plant, root zone depth, root area density profile (RAD) and leaf area density profile (LAD).

In previous versions, 3D-plants did already allow the remodelling of the distribution of LAD cells and thus the shape of a tree. The cells themselves, however, were not part of the tree but instead acted as individual leaves. With the new advancements, LAD cells are now part of a bigger object, which allows the evaluation of a plant as an organism (Simon, 2016).

In Albero, different to the 1D vegetation, it is possible to define the center of the plant (tree) and ENVI-met build up the tree in the model with a grid resolution of 1m x 1m to define trees. The advantage of the new editor is that the trees can be visualized in 3D and the geometrical form is automatically adjusted based on your model resolution (Simon, 2016). On the other hand, it requires more handwork to design the trees from the scratch or to change values from each cells (Bruse, 2017).

Using Albero, three type of trees were created: T1 with sparse canopy form (Figure 3a), T2 with spherical canopy form and uniform distribution inside the crown (Figure 3b) and T3 with spherical canopy form and leaf density concentrated in the outer part of the crown (Figure 3c). In all typologies, trees are 20m high, diameter of 17m, and leaf density starting 4m above the ground to avoid obstruction for wind flux at pedestrians' level. The average LAD considered was 1,2 m<sup>2</sup>/m<sup>3</sup>, based on LAI measurements at Trianon Park with hemispherical images method (Shinzato *et al.* 2013).

<sup>1</sup> LAD is a parameter defined as the total one-sided leaf area (m<sup>2</sup>) per unit layer volume (m<sup>3</sup>) in each horizontal layer of the tree crown (Lalic and Mihailovic, 2004).

The new typologies created were used during the calibration process of the ENVI-met model, in order to obtain the adjustment of the measured and simulated curves at Trianon Park.

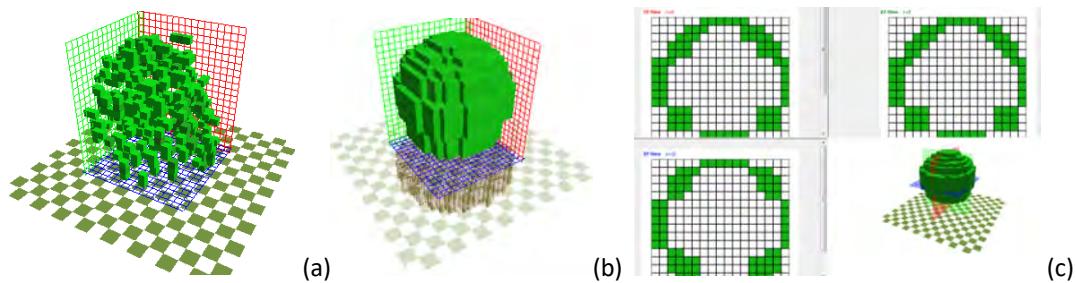


Figure 3. Tree typologies using Albero; (a) sparse canopy form; (b) spherical canopy; (c) spherical canopy with LAD in the outer part of the crown.

#### **Calibration Process in ENVI-met V4**

Simulation of the study area (base case scenario) in ENVI-met V4 was built with input area domain formed by two central blocks representing Trianon Park with 165m x 120m (19.800m<sup>2</sup>) each and 18 blocks around the park. The total area for the modelling was 490.000m<sup>2</sup> with a grid of 200 x 200 cells and each cell with dimension of 3,5mx 3,5m. Five empty cells were added in the border of modelling area and no nesting grid cells were considered. The vertical model had 30 grid cells with 2,5m each.

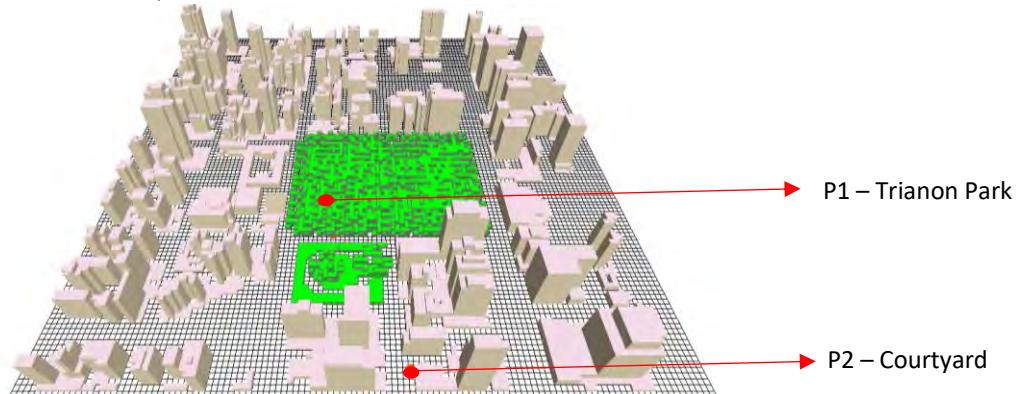


Figure 4. Base case scenario with 2 receptors coinciding with the meteorological stations located at Trianon Park (P1) and Paulista Courtyard (P2)

In order to compare the results of a numerical simulation with measured data or to simulate a specific meteorological development it is necessary to force the simulation by adjusting the variables at the inflow boundaries of the model. With "forced (closed)" boundary condition, the values of the 1D model are copied to the grid cells at the inflow boundary of the model (Huttner, 2012).

The simulations used full-forcing feature, which enables the model to run with predefined boundary conditions for air temperature, wind speed, wind direction, relative humidity, direct radiation, diffuse radiation, longwave radiation and cloud cover. Microclimatic data were obtained from onsite measurements and radiation data from Micrometeorology Group in the Institute of Astronomy, Geophysics and Atmospheric Sciences - IAG at the University of Sao Paulo.

For the input data, the soil temperature for the upper layer was measured using Campbell 107 temperature probe and humidity was estimated from results of Simple Biosphere Model – SIB2, provided by Laboratory of Climate and Biosphere – LBC Group in the Institute of Astronomy, Geophysics and Atmospheric Sciences - IAG at the University of Sao

Paulo. The specific humidity at 2500m was obtained from local Campo de Marte Airport<sup>2</sup> (ca. 3.3km North of the site).

The calibration process was important as the adjustment between the simulated data considered two distinct conditions: one with dense vegetation (P1) and another area without vegetation (P2). The phase with the sensitivity tests simulated scenarios with the three typologies of trees created, adjusting values of LAD, albero and soil moisture.

Simulations ran for 24h, starting on April 4<sup>th</sup> 2016 at 5h and the Figure 5 shows the best results for air temperature achieved during calibration process. For the Trianon Park, the tree typology T3 with LAD of 1,7 m<sup>2</sup>/m<sup>3</sup> in the outer part of the crown had the closest results with the field measurements inside the park.

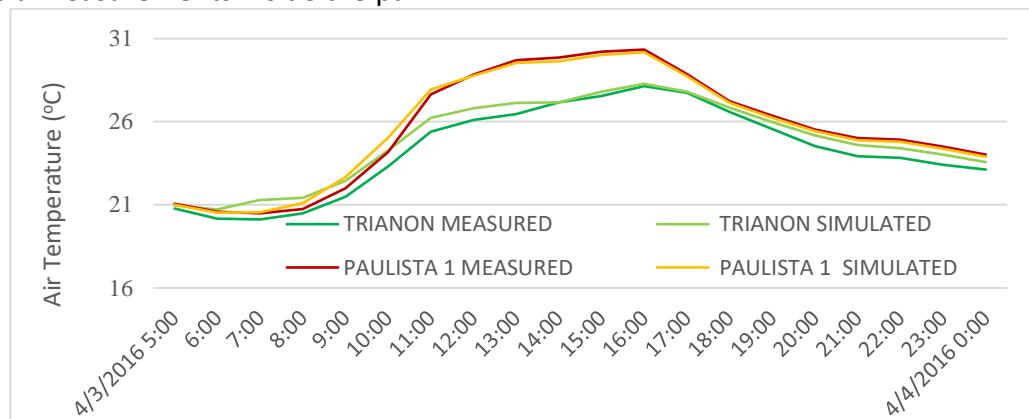


Figure 5. Results for simulated air temperature in ENVI-met and the data measured for meteorological stations - model calibration process.

Based on simulation results, the average difference between air temperatures under dense trees (T3) and the surroundings is up to 1,6 K. The specific humidity under the tree canopy was 12,5 g/kg, while inside the blocks it was 10,90 g/kg. For surface temperature, the vegetation showed an average difference of 10,2K between green spaces and the street. According to the Figure 5, there was a high agreement between ENVI-met simulation results and on-site measurements. Regarding the spatial distribution, results showed that the maximum effect of vegetation in air temperature occurred under the canopies, but the cooling effects could influenced up to 250m in leeward side of the park (Figure 6).

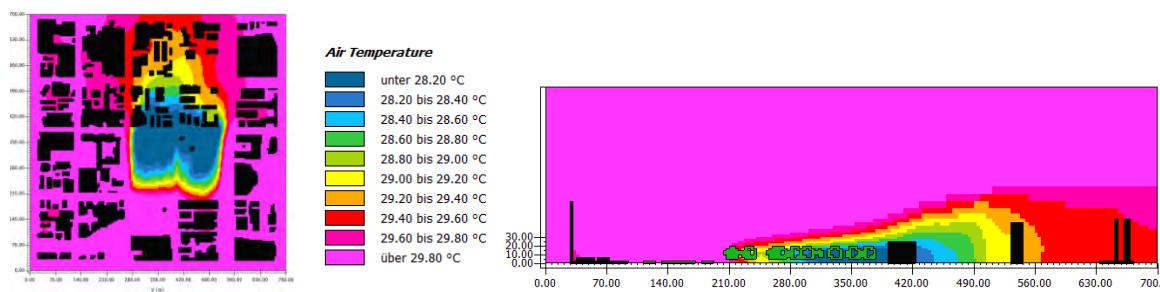


Figure 6. Simulation results for air temperature at Trianon Park – on April 3<sup>rd</sup> 2016 at 15h.

### Simulations with new green areas

According to the results of the calibration process, the vegetation effect was restricted to the location of the park. In this way, a new scenario was created in order to verify the effect of vegetation by increasing the green areas area inside every block. The configuration of each

<sup>2</sup> Available from the homepage of atmospheric soundings by University of Wyoming. Access on <http://weather.uwyo.edu/upperair/sounding.html>

block was maintained and the vegetation were placed only in unbuilt areas between buildings (Figure 7a).

The proposed new green areas were formed of dense tree groups with grass covering the open soil. Based on the T3 typology, which had rounded canopy with LAD of  $1,7 \text{ m}^2/\text{m}^3$  in the outer part of the crown (20m height/ 14m diameter), two other tree typologies were created: T4 with LAD of  $1,5 \text{ m}^2/\text{m}^3$  (15m height/ 11m diameter) and T5 with LAD of  $1,2 \text{ m}^2/\text{m}^3$  (10m height/ 7m diameter). The trees of the park were replaced by grass to avoid influencing the results on the surroundings.

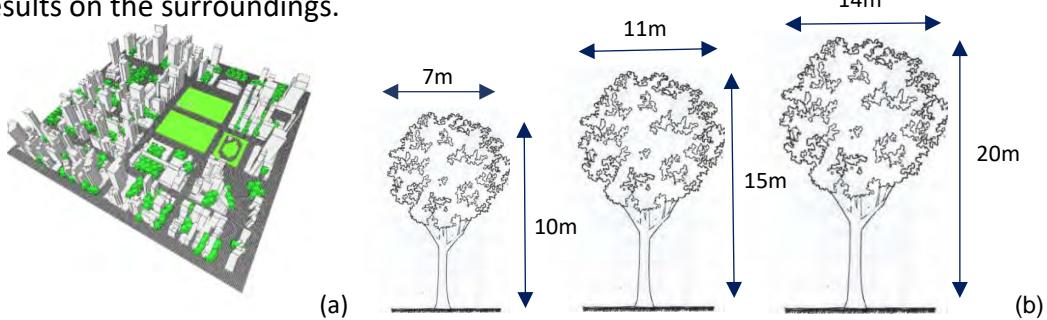


Figure 7. (a) Scenario with trees inside the blocks; (b) Trees typology: T5, T4 and T3, respectively.

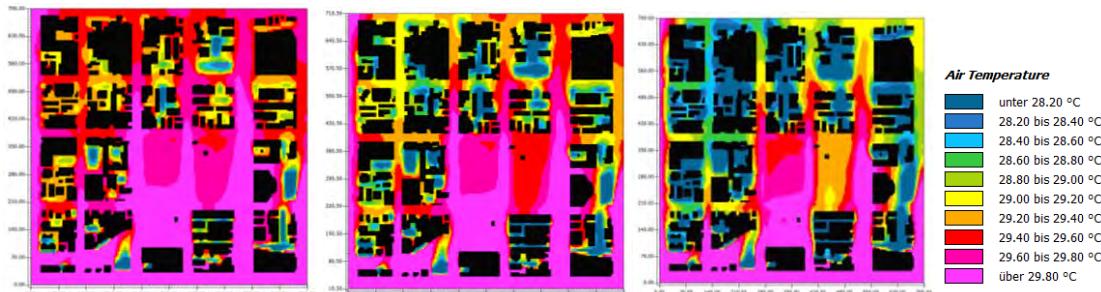


Figure 8. Results for air temperature with typology T5, T4 and T3, on April 3<sup>rd</sup> 2016 at 15h – z=1.25m.

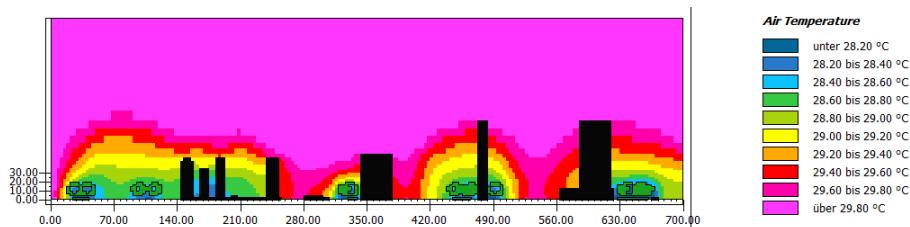


Figure 9. Results for air temperature for trees inside the blocks (grass + T3 LAD  $1,7 \text{ m}^2/\text{m}^3$ ) – Section axes x-z at grid 123 (432.25 m).

The cooling effect of vegetation depends on urban configuration, soil characteristics, leaf density and green areas distribution. The maximum reduction in air temperature under the trees was 1,6 K, on April 2016 at 15h, represented in dark blue spots in Figure 8.

In those areas, the specific humidity under canopy was 12,5 g/kg and the lowest value registered inside the block was 10,6 g/kg. For surface temperature, simulations showed differences up to 13,6 K and for mean radiant temperature MRT, the reduction was up to 10,5K.

Comparing the three scenarios, the maximum effect in air temperature occurred in 20% of the total unbuilt area using T5 trees, while the groups of T4 had 75% and 90% with T3 typology. In this sense, spatial configuration of the maximum effect with T3 trees was more pronounced and homogeneous than the other two situations.

## Final Considerations

After the calibration process between measured and simulated data in ENVI-met 4, with full-forcing feature and the new resources of the Albero module for 3D trees, simulations of the study area were developed with the inclusion of new green areas in the built-up blocks surrounding Trianon Park. According to the simulations, for different canopy characteristics, results indicated a very good agreement between the ENVI-met model and the local measured data, with a maximum reduction of 1,6K in air temperature and 13,6K for surface temperature, when comparing the base case to dense trees inside the blocks (T3 typology).

The cooling effect from Trianon Park on surrounding urban area was up to 250m in leeward side of the park, while small green areas simulated could reach up to 30m. However due to a better vegetation distribution, the cooling effect of small green areas was well distributed and more homogeneous than one single park.

From the analysis of the results, it could be seen that greening the unbuilt areas between buildings can be an effective strategy to ameliorate the microclimatic conditions at Bela Vista borough, in downtown São Paulo, considering the potential of vegetation in reducing urban warming, especially in the daytime.

## Acknowledgments

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## References

- Bruse, M., Fleer, H. (1998). Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model. *Environmental Software and Modelling*, 13, 373-384.
- Bruse, M. (2004). ENVI-met implementation of the Jacobs A-gs Model to calculate the stomata conductance. Retrieved on February 2017 from: <http://www.model.envi-met.com/>
- Bruse, M. (2017). ENVI-met website (n.d.). Retrieved on February 2017 from: <http://www.model.envi-met.com/>
- Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M., Demuzere, M. (2013). Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. *Progress in Physical Geography*, 37(1), 2–28.
- Huttner, S. (2012). *Further development and application of the 3D microclimate simulation ENVI-met*. PhD. Johannes Gutenberg Universität-Mainz.
- Jacobs, C.M.J. (1994). Direct Impact of Atmospheric CO<sub>2</sub> Enrichment on Regional Transpiration. PhD. Wageningen Agricultural University.
- Lalic, B; Mihailovic, D. T. (2004) An empirical relation describing leaf-area density inside the forest for environmental modelling, *Journal of Applied Meteorology*, 43(4), 641-645
- Oke, T. (1978). *Boundary layer climate*. London: Methuen & CO
- Shinzato, P.; Duarte, D.; Barros, F.; Moreira, D. (2013). Intensity and Spatial Influence of Urban Parks: a case study in São Paulo, Brazil. In: *Sustainable Building Conference 2013, Graz, Austria, 2013*, Construction Products and Technologies.
- Simon, H. (2016). *Modeling urban microclimate*. PhD. Johannes Gutenberg Universität-Mainz.
- Stone, B. (2012). *The City and the Coming Climate: Climate Change in the Places We Live*. New York: Cambridge University Press.
- Voogt, J.A.; Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, 86, 370–384.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Resilience in Latin America: exploring flooding mitigation in Bogotá (Colombia)

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**Abstract:** This paper is concerned with the implications of flooding in Bogotá (Colombia) by focusing on a specific typology of flooding -surface water flooding- resulting from excess of surface water runoff as it occurs in the Colombian capita. In particular, the paper considers some of the main alternative strategies that can be used to reduce the risk of surface water flooding and pays specific attention to the benefits of Sustainable Urban Drainages (SUDS). The suitability of SUDS in the urban context is tested through an approach focusing on the city block scale and its surfaces' characteristics. Technical and social elements of SUDS are critically analysed and accordingly, a comparative analysis is performed to test different adaptive strategies scenarios for a case study in quartier Carimagua in the inner urban area of Bogotá. Carimagua barrio has been found to be able to effectively mitigate the excess of surface water runoff, and by so to meet some of the challenges associated with climate change. On this basis, it is defended that the city block can cope with not only its own surface water runoff but also to compensate as active catchment for other parts of the city where adaptation might not be feasible.

**Keywords:** climate change, flooding mitigation, urban resilience, permeability, sustainable urban drainages.

### Introduction

This paper will focus on the drainage capacity of neighbourhoods of Bogotá to give some answers to the risk of flooding caused by climate change phenomenon. For this reason, this paper engages with future climate change and specifically with predicted increased risk of flooding, with specific focus to test flooding mitigation techniques in the increasing urbanised land of Colombia, and Latin America in general.

From 2010 to 2011 La Niña phenomenon affected Colombia and caused economic losses caused by flooding, related to the destruction of infrastructure and urban areas. A paradigm shift in water management is recognized as a necessary step for adaptation to climate change and crucial for furthering the sustainability agenda in Bogotá. On this regards, research conducted (Hoyos et al; 2013) emphasized the importance of both the spatial context as well as the variables related to hazard exposure and social vulnerability (figure 1). Melgarejo et al. (2014) stress this point in view that extreme weather events are becoming disaster management systems in the city.

Effects of climate change in Colombia have been modelled (IDEAM et al; 2015) and a generic change in temperature and rainfall is expected to increase the climatic variability effects of El Niño and La Niña, which have an exacerbated impact in Colombia and Latin America in general. In the Cundinamarca region, where Bogotá is located, it has been predicted an increase in average temperatures by 2100 to up to 2.3°C against today values.

Also it has been predicted a change in the precipitation patterns: an increase in rainfall to up to 30% in the province of Bogotá North, with values between 10% and 30% compared to today's values (IDEAM et al; 2015). Some of the effects of such changes are expected to affect the farming sector due to both changes in temperatures as well as infestation associated with increased rainfall. Also, infrastructural sector (transport and energy) are expected to fail (IDEAM et al; 2015) with potentially devastating effects on population (when this is associated with population security).

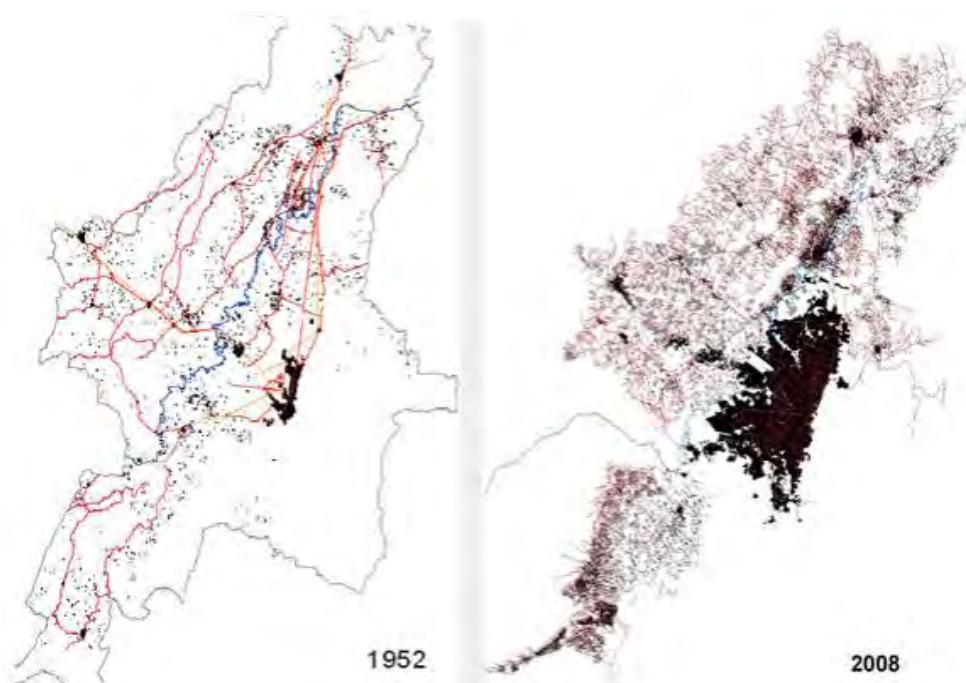


Figure 1. Land urbanisation and density evolution of Bogotá (Niño, 2012).

The Colombian disaster risk management ministry (UNGRD), in cooperation with other international organisations, are implementing the project "Strengthening the risk management capacity of Floods" in order to create directives to cope with excess rainfall and the necessary standards to control this kind of events, by means of identifying four flooding risk scenarios: (a) first, ponding water, (b) second, flooding, (c) third, electrical storms (d) tree-falling. These scenarios are connected to three climate phenomena, i.e. hailstorm, landslides and gales (INDIGER, 2016).

To mitigate these changes, and specifically with the predicted increase rainfall, an adaptation technique is required. Techniques available to mitigate with the excess water runoff are the sustainable urban drainage systems (SUDS), which are non-piped drainage systems that minimise the impact of surface water runoff (rainfall that cannot infiltrate the soil). According to Toledo (2012), SUDS that are most sustainable and suitable to urban environment are green roofs and pervious surfaces. Pervious surfaces effectively reduce surface water runoff and pollution to a significant extent.

On the other hand, green roofs represent a cheap, relatively good option to reduce surface water runoff. In fact, they reduce surface water runoff to a more limited extent when compared to previous surfaces, but they can add benefits not only regarding pollution reduction, but also regarding biodiversity, wildlife, amenity, health, reduction of urban heat island effect.

Related, green roofs increase the life of roofing materials, reduce the urban heat-island effect (Ritchie & Thomas, 2013) and reduce the energy demand (GLA, 2011). This paper aims at contributing to the development of an adaptation strategy within Bogotá by producing a strategic test of adaptation to flooding strategy that effectively mitigates with the predicted increase of rainfall in the Province of Bogotá.

## Methods

To analyse closely this phenomenon as it occurs, it has been selected an urban area in Bogotá, the Carimagua neighbourhood. This quartier was founded in 1967 and was an example of social housing in Bogotá composed of 1108 single-family homes.

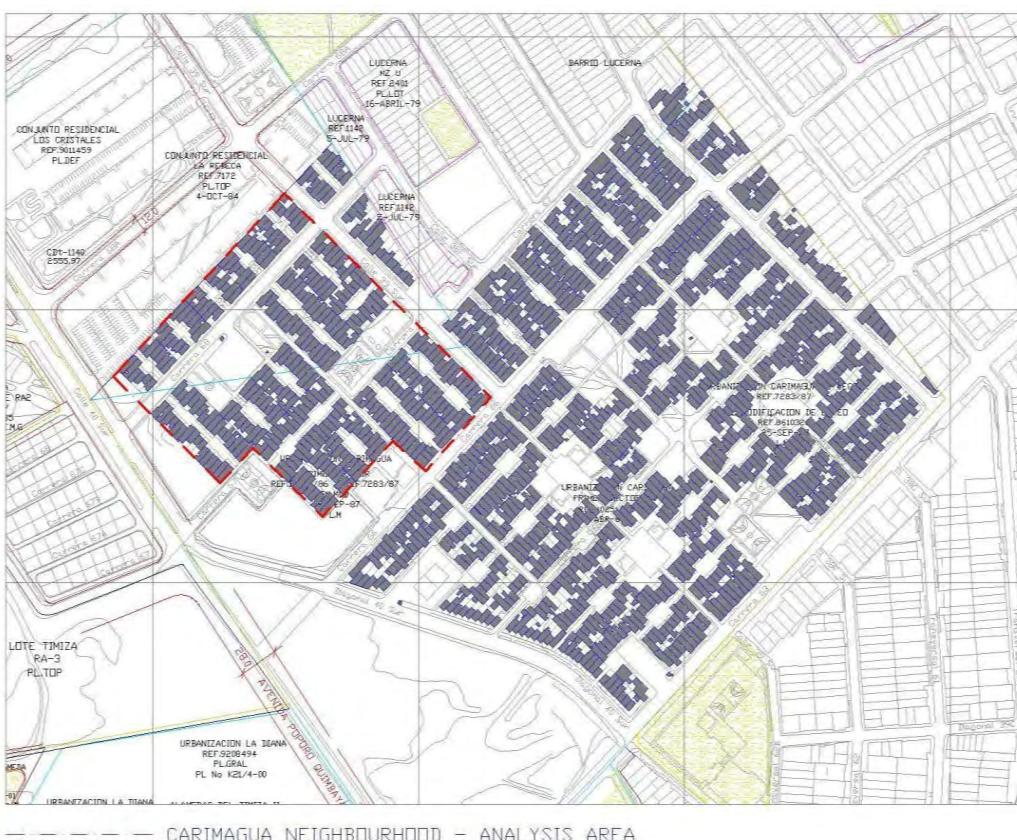


Figure 2. Carimagua neighbourhood: analysed portion evidenced.

Currently, the houses are transformed according to the needs of the inhabitants; however, the urban structure is maintained (figures 3 and 4). On the other hand, Carimagua neighbourhood is in a middle-high flooding risk area, and this paper intends to respond to the following question: is the urban barrio of Carimagua able to mitigate the predicted 30% rainfall increase?



Figure 3. Carimagua neighbourhood in 1967 (left) and today (right).



Figure 4. Carimagua neighbourhood, examples of adaptive initiatives.

To respond to such question, a critical analysis of flooding mitigation strategies to retain rainfall is performed in order to identify which devices are the most suitable ones in terms of costs and benefits (i.e. cost, maintenance, land-take, peak flow reduction and volume reduction) and in terms of extra benefits (i.e. pollution reduction, landscape/wildlife/amenity benefit), as shown in figure 5.

Secondly, an analysis of the case study city block has been carried out. In this context, it is being performed a comparison of the effects of water runoff mitigation of the city block by reducing the degree of impermeability of the surfaces according the use of different finishing surfaces' permeability, as proposed on a recent publication by Ritchie & Thomas (2013), see figure 6, with the value 1.00 being completely impermeable and 0.00 being completely permeable and hence desirable. This city block calculation is aimed at assessing SUDS-based strategies that can be followed to reduce the surface water runoff (i.e. to increase their permeable degree and reduce their impermeable degree).

techniques	investment & benefits						extra benefits	
	surface water runoff reduction							
	capital cost	maintenance	land-take	peak flow reduction	volume reduction	pollution reduction		
SUDS	GREENROOFS	low-high	medium	none	medium	medium	✓	
SUDS	BIORETENTION	low	medium	high	medium	medium to high	✓	
SUDS	DETENTION BASINS	low	low	medium	good	low	✓	
SUDS	PONDS	medium-high	medium	high	good	low	✓	
SUDS	STORMWATER WETLANDS	high	medium-low	high	good	low	✓	
SUDS	FILTER STRIPS	low	low	high	low	low	✓	
SUDS	SWALES	low	medium	high	medium	medium	✓	
SUDS	INFILTRATION BASINS	low	low	high	good	good	✓	
SUDS	INFILTRATION TRENCHES	low-medium	medium	low	medium	low	✓	
SUDS	SOAKAWAYS	low	low	low	good	good	✓	
SUDS	PERVIOUS SURFACES	low-medium	low	none	good	good	✓	
SUDS	SAND FILTERS	low	high	low	low	low	✓	
SUDS	GEOCELLULAR MODULAR SYSTEMS	low	low	low	good	low		
SUDS	RAINWATER HARVESTING: water butts	low	low	none	low	low		
SUDS	RAINWATER HARVESTING: big tanks	high	medium	none	high	high		
traditional	TRADITIONAL PIPED SEWER	high	high	none	low	high		

Figure 5. SUDS analysis of suitability to mitigate surface water runoff in urban areas.

Accordingly, it has been performed an inventory of surfaces materials within a selected area of Barrio Carimagua (figure 2) to then proceed to calculate the overall degree of permeability based on the degree of permeability of each material. This step required to quantify the area of all the surfaces within the city block (such as roofs, pavements, backyards, etc.) and multiply them by the degree of impermeability of the characterising material, as listed in figure 6. This provided a numerical result that is the *overall degree of impermeability*, which for the selected case study is 0.9.

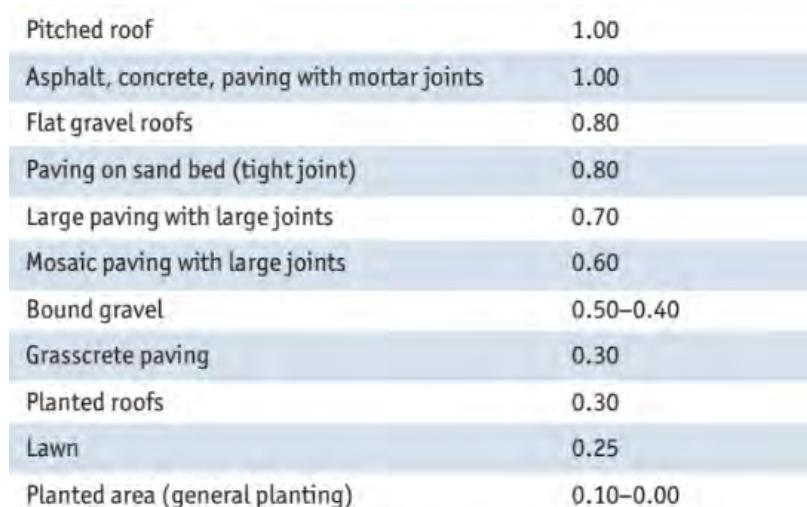


Figure 6. Degree of impermeability of different materials (Ritchie & Thomas, 2013)

Hypothesising the need to cope with 30% increase rainfall, a strategy to reduce such degree of impermeability by the 30%, a new goal of *overall degree of impermeability* to 0.6 for the selected case study is been pursued. This new degree of permeability of the city block will be calculated by changing materials to the surfaces and applying new degrees of permeability as listed in guidance for sustainable urban design (Ritchie & Thomas 2013).

To evaluate the efficiency and feasibility that the proposed devices (green roofs and pervious surfaces) have in reducing the surface water runoff, a selection of strategies were conducted to deliver a new value of impermeability after the surface-materials were substituted by green roofs and pervious surfaces.

Finally, by building on the results achieved in the previous steps, it is presented a critical discussion of the advantages and disadvantages of this adaptation strategy within the city of Bogotá.

## Results

Adaptation of the city block with sustainable urban drainages has been performed, and three possible adaptation scenarios were explored to achieve the aspiring 30% permeability increase to cope with predicted excess rainfall (see Table 1 below).

The first scenario (strategy A) modifies the degree of permeability of the publicly owned areas (streets and parking) by replacement of the (impermeable) cement and asphalt to a permeable parking and permeable asphalt. This strategy achieved the desired *overall degree of impermeability* of 0.6 (see first shaded column in table 1).

The second scenario (strategy B) modifies the degree of permeability of the privately-owned areas (within the plots) by retrofitting roofs to green roofs and by adding planted areas in the front gardens. This strategy also achieved the desired *overall degree of impermeability* of 0.6 (see second shaded column in table 1).

The third scenario (strategy C) combines both the previous strategies, and it has shown that an outstanding 52% increased permeability, equal to an overall degree of impermeability of 0.3 (see last shaded column in table 1).

Table 1. Calculation of improved permeability in Carimagua city block.

Existing situation (Carimagua city block)					need for adaptation (imperviousness reduced by 30%)					
	area (m <sup>2</sup> )	% of total area	degree of imperm.	degree of imperm. (*surface)	strategy A: public	strategy B: private	strategy C: both	degree of imperm.	degree of imperm. (*surface)	degree of imperm. (*surface)
Streets and Parkings (asphalt)	12324	32%	1	12324	0.3	3697	1	12324	0.3	3697
flat roofs (Fibre cement)	9792	26%	1	9792	1	9792	0.3	2938	0.3	2938
Green areas (lawn)	7380	19%	0.25	1845	0.25	1845	0.25	1845	0.25	1845
Backyard (concrete)	5760	15%	1	5760	1	5760	1	5760	0.6	3456
front gardens (concrete)	2880	8%	1	2880	1	2880	0.3	864	0.3	864
<b>overall degree of impermeability</b>				<b>0.9</b>	<b>0.6</b>	<b>0.6</b>	<b>0.6</b>	<b>0.3</b>	<b>0.3</b>	<b>0.3</b>
					23%		23%		52%	
						more permeable	more permeable	more permeable	more permeable	more permeable

## Discussion

From the physical realm point of view, the results proposed show that effective adaptation strategies to cope to increase rainfall are feasible, in different ways and in different degrees. However, inhabited built environments are known to present different levels of organisations, so it is recognise that while numerically adaptation is feasible, shortcomings should be expected when implementing these in a real project.

With specific regards to Barrio Carimagua, since its construction, this quartier has embedded continuous modifications and transformative processes, because of the nature of this type of social housing in Colombia (Cubillos, 2006). These processes are expected to facilitate adaptive strategies. In fact, in Barrio Carimagua is has been found feasible some different strategies of flooding adaptation, according to the owners' preferences; i.e. some owners might opt for green roofs and benefit also from the improved thermal comfort with the homes; some might opt for an internal garden). Where no action is preferred, the government can still opt to adapt communal spaces such as parking spaces.

Strategies deployed to increase permeability increase are successful. With the strategies used, the percentage of permeability is increased by 23 percent. It has been possible to increase the total permeable area by 52 percent combined different strategies.

In the parking area it is suggested to change the soil cement by a semipermeable material that improves the permeability percentage but maintains the mechanical properties similar to those of the current cement. And to the extent possible, it is proposed to recover the original garden of the facade to recover the green areas and increase the area of permeability.

## Conclusion

This study identifies the importance of satisfying the need for permeable urban areas today in Bogotá, and consequently, the results propose to implement a model that can respond to such a need, and to implement and optimise life conditions of an urban habitat.

Green roofs constitute an adequate and economical strategy that substantially contributes to increasing the percentage of permeable area in Bogotá and Carimagua neighbourhood is a good example of this adaptability. Also, it could be used as an urban vegetable garden where some vegetables, water retention plants and aromatic plants could be planted.

In Carimagua neighbourhood is evident the demand for habitable soil, because residents tend to occupy all the open spaces available within the plots by physically building on front garden and backyard, with a change use of the plot area, different than the one initially designed. This is a general phenomenon in Bogotá and also other Latin American cities.

It is recognised the limits of this research: while it is used a 30% increase in rainfall is considered over a year, the time factor is not be considered. More research is needed to evaluate the rainfall as it occurs in a short amount of time and test the validity of the present research with the effect of a storm. This could lead to a combined strategy in the outskirts of the urban areas to apply other integrative strategies such as large water reservoirs. However, the ultimate aim of this research is to propose a starting point of adaptive strategies in Latin American urbanised contexts in a moment when heavy urbanisation is occurring and recommendations and guidelines being produced.

Further research is oriented at proposing a factorial model in the study regarding the degree of relationship between variables and factors contributing to increasing resilience to flooding. In this model, variables such as permeability, porosity, percentage of drainage, percentage of runoff and humidity will be interrelated.

## References

- Cubillos-González, R.A., 2006. Vivienda social y flexibilidad en Bogotá. Bitácora, 10(1), pp.124–135.  
Available at: <http://www.revistas.unal.edu.co/index.php/bitacora/article/view/18717/19614>.

- GLA, 2011. The London Plan.
- Hoyos, N. et al., 2013. The impact of the 2010-2011 La Niña phenomenon in Colombia, South America: The human toll of an extreme weather event. *Applied Geography*, 39(September 2011), pp.16–25. Available at: <http://dx.doi.org/10.1016/j.apgeog.2012.11.018>.
- IDEAM et al. 2015. Nuevos Escenarios de Cambio Climático para Colombia 2011-2100 Herramientas Científicas para la Toma de Decisiones – Enfoque Nacional – Departamental: Tercera Comunicación Nacional de Cambio Climático. [http://documentacion.ideam.gov.co/openbiblio/bvirtual/022964/documento\\_nacional\\_dep\\_artamental.pdf](http://documentacion.ideam.gov.co/openbiblio/bvirtual/022964/documento_nacional_dep_artamental.pdf)
- IDIGER, 2016. Plan de contingencia 2da temporada de lluvias y posible fenómeno de la niña 2016. [online], Alcaldía Mayor de Bogotá. Available at: [https://issuu.com/fopae/docs/plan\\_de\\_contingencia\\_2da\\_temporada](https://issuu.com/fopae/docs/plan_de_contingencia_2da_temporada) [Accessed March 5, 2017].
- Melgarejo, L.F. & Lakes, T., 2014. Urban adaptation planning and climate-related disasters: An integrated assessment of public infrastructure serving as temporary shelter during river floods in Colombia. *International Journal of Disaster Risk Reduction*, 9, pp.147–158. Available at: <http://dx.doi.org/10.1016/j.ijdrr.2014.05.002>.
- Niño FIERRO, K.N., 2012. Análisis para la gestión del riesgo de inundaciones en Bogotá: Un enfoque desde la construcción social del riesgo. Universidad Javeriana, sede Bogotá. Available at: <https://repository.javeriana.edu.co/bitstream/handle/10554/15414/NiñoFierroKarenNatalia2012.pdf?sequence=1&isAllowed=y>.
- Rojas, C., De Meulder, B. & Shannon, K., 2015. Water urbanism in Bogotá. Exploring the potentials of an interplay between settlement patterns and water management. *Habitat International*, 48, pp.177–187.
- Romero-Lankao, P. et al., 2014. Scale, urban risk and adaptation capacity in neighborhoods of Latin American cities. *Habitat International*, 42, pp.224–235. Available at: <http://dx.doi.org/10.1016/j.habitatint.2013.12.008>.
- Romero-Lankao, P., Hughes, S., Qin, H., Hardoy, J., Rosas-Huerta, A., Borquez, R., & Lampis, A. (2014). Scale, urban risk and adaptation capacity in neighborhoods of Latin American cities. *Habitat International*, 42, 224–235. <https://doi.org/10.1016/j.habitatint.2013.12.008>
- Ritchie, A. & Thomas, R., 2013. Sustainable Urban Design. [online], Taylor & Francis. Available at: <http://www.myilibrary.com?ID=552979> [Accessed March 5, 2017].
- Toledo, L., 2012. Adaptation to flooding within the city block scale. 1<sup>st</sup> International Conference on Urban Sustainability and Resilience. UCL, London.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Vertical Farms: Historic Development, Current State and Future Directions

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**Abstract:** Population growth and decreasing levels of land availability is driving our ever-growing society to consider more efficient strategies to produce food. The current state of the depleting natural resources and the straining on the Earth's capacity is putting pressure towards achieving a truly sustainable urban development. Cities will continue to grow hence it is imperative to find solutions to minimise the impact that human development has on the planet. The integration of agricultural and green elements in general, such as vertical farms and green walls/roofs etc., into the built environment has the potential to minimise the damage caused by extensive urbanisation. In particular, Vertical Farming can help towards tackling important issues such as food scarcity, water/flood management and more, offering manageable solutions especially when developed in conjunction with a holistic architectural and urban design approach. This study outlines the current trends and obstacles of vertical farms' development. The following stage of this investigation will be to propose suitable future scenarios for the Vertical Farming concept, based on real case studies, experimental fieldwork and computer simulations. This article is the first step of a larger research project where the potential of vertical farms is explored along their integration within cities.

**Keywords:** Vertical Farming (VF), Urban Agriculture, Biomimicry

### Introduction

Our ever-growing society urgently needs to find better strategies to achieve a sustainable balance between urban development and the protection of the natural environment (Hasse & Lathrop 2003; Johnson 2001). Cities will continue to grow and it is imperative to find solutions to minimise the impact that buildings and cities have on the planet (Al-Chalabi 2015; Johnson 2001). The integration of greenery into the built environment has the potential to minimise the damage caused by extensive urbanisation (Alexandri & Jones, 2008; Safikhani et al, 2014). Nature has inspired humans to find solutions to a number of problems, this is also known as Biomimicry (Lurie-Luke 2014). This concept helps to promote a holistic relationship between plants and architecture. There are a number of examples within architecture where this relationship has been established (Pawlyn 2011; El-Zeiny 2012). This research intends to undertake a deeper exploration in this area, with a particular focus on Vertical Farming, which will be referred to as VF in this paper (Despommier 2009; Despommier 2010; Sarkar & Majumder 2015).

Using nature inspired solutions to tackle modern problems represents a significant source of knowledge-transfer opportunities, as other research have demonstrated through biomimicry (Breuste et al, 2013b; El-Zeiny, 2012; Pawlyn, 2011). However, despite all the advances and research undertaken evaluating the integration of green elements in cities, less sustainable practices are predominant and more research is required (Breuste et al,

2013a). This is particularly true in the area of VF, where regular unsustainable agricultural practices are most common. This research will pay particular attention to the best integration of Vertical Farms (VF) in cities.

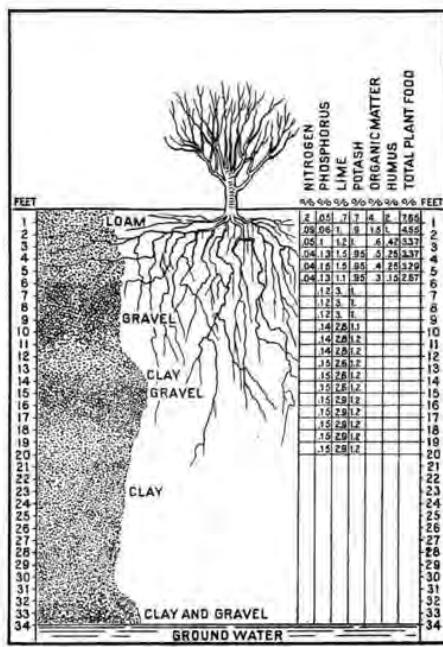
The main aim of this paper is to investigate the current development of VF in order to identify the obstacles faced by their integration with architectural design and urban areas. The purpose is to identify the main characteristics that will help to achieve and maximise an overall sustainability of VF integrated into the built environment, starting with in-depth investigation of the relationship between *vertical farms* and *architecture*. The target is to analyse the feasibility of VF integration and establish the most suitable routes to achieve a cohesive urban integration of these two concepts. Therefore, this study aims to investigate current progress of VF and urban agriculture through literature review, analysis of several real VF case studies at different locations, site-visits, own experimental VF field work and computer simulations. This paper covers mainly the first part of this research project: gathering, analysis and discussion of the information found during the literature review. Further research papers will be published with the progress of this investigation.

### **Historic Development of Vertical Farming**

Research has found that green infrastructure in cities helps to mitigate a number of issues in urban areas, such as Urban Heat Island (UHI) Effect, water/flood management, amongst other (Breuste et al. 2013a). Vertical farms have the potential to add to these benefits, moreover they could also help to solve further problems, such as food scarcity, agricultural land availability and more (Hasse & Lathrop 2003). Nature has inspired humans to find solutions to a number of problems (Lurie-Luke 2014) and there are a number of examples within architecture where the integration of plants provided the best solutions to specific problems (Pawlyn 2011; El-Zeiny 2012). Published literature supports the concept of VF to help solving some of these issues (Despommier, 2010; Garg & Balodi, 2014; Sarkar & Majumder, 2015). In brief, nature inspired solutions in the area of plants and architecture offer a significant source of knowledge-transfer opportunities, as other research has demonstrated (Breuste et al. 2013b; El-Zeiny 2012). Cities should learn to behave as ecosystems rather than parasites, vertical farms can help to achieve this principle (Despommier 2013).

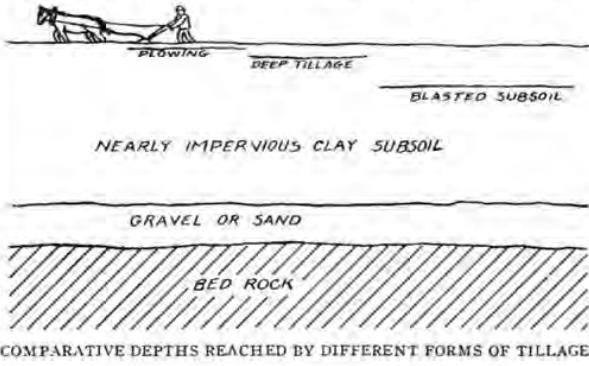
Historically, the term ‘Vertical Farming’ originated back in 1915, it was used in a publication by Prof Gilbert Ellis Bailey, a Professor of Geology at the University of South California (Bailey 1915). The title of his book is *Vertical Farming*, where he used this term mainly to describe a soil-based type of agricultural development. In his book, Professor Bailey explores a number of issues, mainly related to several of the characteristics and properties of agricultural soil, such as soil texture, chemistry, soils moisture, etc. He concluded his book by establishing that with the use of inexpensive explosives, farmers can effectively farm deeper into the soil layers. Thus, increasing the acreage available in their fields and therefore obtaining larger crops (Bailey 1915). Despite of the fact that this book does not use the term of VF as it might be perceived nowadays (Despommier 2010; Sarkar & Majumder 2015), with his concepts, Professor Bailey created a foundation of a concept that will thereafter be shared with the modern understanding of VF:

“Instead of spreading out over more land he [the farmer] concentrates on less land and becomes an intensive rather than extensive agriculturist” (Bailey 1915).



THE DEEPER PLANT FOOD MIGHT JUST AS WELL BE IN EUROPE FOR ALL THE ATTENTION THAT IS USUALLY GIVEN IT

**Benefit of Using Explosives.**—It is admitted that present methods of cultivation do not go deep enough, and it must also be admitted that the use of specially prepared agricultural explosives offers the desired remedy. It is admitted by all



authorities in agriculture that the plow and harrows do not go deep enough and they advise the use of subsoilers. Scores

Figure 1. Diagrams and passages from Prof Bailey's Book, pages 25 & 63 (Bailey, 1915)

In this first book on VF, the author was talking about intensive agriculture in a reduced area of land, in terms of deeper levels into the ground. The modern concept of VF aims to achieve a similar outcome, but instead of using explosives to reach deeper layers of soil, modern vertical farms commonly use the vertical stacking of layers of crops (Despommier 2009; Banerjee & Adenaeuer 2014), by using a number of different techniques, such as hydroponics, aeroponics, aquaponics, etc. (Besthorn 2013; Fischetti 2008) without the use of explosives of course! Furthermore, modern vertical farms are not required to be underground, they can also be above ground, as well as indoors or outdoors. Briefly explained, *hydroponics* "is a method of growing whereby the plants roots are directly exposed to water based, nutrient rich, solutions without using, or needing, a soil or coco medium"(Holland Hydroponics & Horticulture, 2016). *Aeroponics* is also a soil-less method of growing plants, which "uses small microjets to spray the plants' roots with a fine, high-pressure mist that contains nutrient rich solutions."(pH Hydro 2014). Finally, *Aquaponics* "is the combination of aquaculture (raising fish) and hydroponics (the soil-less growing of plants) that grows fish and plants together in one integrated system. The fish waste provides an organic food source for the plants, and the plants naturally filter the water for the fish."(The Aquaponic Source 2017 2017).

The current concept of vertical farms gained new momentum particularly in 1999, with the theoretical work undertaken by Dr Dickson Despommier. He is a Professor of Environmental Health Sciences and Microbiology at Columbia University, New York. Dr Despommier explains that "the concept of the vertical farm arose in my classroom in 1999 as a theoretical construct as to how to deal with a wide variety of environmental issues." (Plan 2B Green 2011). There is evidence of some advances in the area of what is currently known as VF before 1999 (Plan 2B Green 2011) , however major theoretical boost in this area only occurred with Dr Despommier's publications and designs, alongside his professional colleagues (Fischetti 2008). He is considered to be the "Father of the vertical farm concept/movement" (Banerjee & Adenaeuer 2014).



Figure 2. Pictures taken by the author during a site visit to GrowUp urban farms in London

The decade following Dr Despommier's work/publications witnessed a dramatic increase in the number of 'real-life' vertical farms developed, also referred to as vertical agriculture, and occasionally denoted as plant factories (Yang 2014). Furthermore, this number continues to increase exponentially and more vertical farm projects are coming to life (Yang 2014; Association for Vertical Farming 2016). Despite all the existing obstacles to develop vertical farms as Dr Despommier initially envisaged (Despommier 2009), further progress in this area has started. Perhaps not quite as large as the ones suggested by him, but projects of 3- to 5-storey facilities can be found in a number of countries around the world, a few perhaps larger (Association for Vertical Farming 2016). Table 1 shows some of the most notorious developments of vertical farms. There are a number of identified obstacles that class VF as an un-common agricultural practice (these will be discussed here at a later stage) and it is evident that more research and expert skills are needed to make it a real possibility to grow larger quantities. Nevertheless, there is irrefutable evidence that the vertical farm concept is rapidly evolving and the obstacles would perhaps become more manageable.

Table 1: Vertical farms around the world

Country	City	Project Name/Organisation	Size/Type
Korea	Suwon	Rural Development Agency	3-storeys
Japan	Kyoto	Nuvege	Plant Factory
Singapore	Lim Chu Kang	Sky Greens	4-storeys
USA	New Jersey	AeroFarms	2,800 m <sup>2</sup> warehouse
Sweden	Linkoping	Plantagon *	17-storeys
USA	Chicago	The Plant	4-storeys
USA	Wyoming	Vertical Harvest	3-storeys
USA	Milwaukee	Growing Power	5-storeys
Holland	Hertogenbosch	PlantLab	Underground Farm
China	Shanghai	Agricultural Science and Technology Co.	Plant Factory

Notes: \* Plantagon: project under planning, not yet built

## **Latest Development on Vertical Farming**

Despite of the significant development on commercial vertical farms (Kozai, et al, 2016; Sarkar & Majumder, 2015; Yang, 2014), there is an evident gap in academic documentation of current advances on VF. Most academic journal papers support common premises stressing the need to encourage further development of vertical farms. Some of the most prominent reasons for these premises are: the lack of land availability, food scarcity and population growth (Sarkar & Majumder 2015; Garg & Balodi 2014; Banerjee & Adenaeuer 2014; Al-Chalabi 2015).

It is frequently stated that the main drivers for the evolution of agricultural research are: 1)Fast growth in science and 2)Technological knowledge (Garg & Balodi 2014; Banerjee & Adenaeuer 2014). The global urbanisation rate is also playing a significant part according to literature, it is predicted that 70% of the population will be living in urban centres by the year 2050 (Al-Chalabi 2015). Furthermore, there is a need to restore the environmental imbalance created by farming chemicals (Garg & Balodi 2014; Despommier 2013). Further issues affecting food demand are the changes in food preferences (Garg & Balodi 2014; Banerjee & Adenaeuer 2014). These changes are arguably the result of the rising per-capita income, particularly in developing countries (Sarkar & Majumder 2015; Garg & Balodi 2014), as well as the increase of purchasing power (Banerjee & Adenaeuer 2014).However, they are also likely to be affected by occupational changes and extended global linkages (Garg & Balodi 2014). It is predicted that by the year 2050 the world will need 60% more food, while figures currently show that 1.3 billion tons of food is lost or wasted every year (Banerjee & Adenaeuer 2014). These later issues are particularly worrying since they show that the main problems affecting food scarcity are not just founded on the depletion of natural resources, but on the lack of efficient management of the available food.

A significant advantage of the vertical farm concept is that they can be located within the urban areas. Therefore, by producing food closer to the end-consumer, the amount of food wasted can be significantly reduced, by decreasing transporting time/distance and also by producing just the right amount for the actual needs of specific locations. This will also help to decrease CO<sub>2</sub> emissions originated from food transport.

The main challenges faced by VF are the high requirements for expert knowledge in plant science and engineering (Sarkar & Majumder 2015). Furthermore, there are a number of practical problems besides the popularly emphasized financial difficulties. Some of the cited challenges are: difficulty to establish an effective and efficient eco-friendly design of vertical farms structures, difficulty to design a well-controlled environment, watering system, monitoring of nutrient solution, selection of ideal crop, etc. (Sarkar & Majumder 2015; Al-Chalabi 2015).

On the other hand, some of the main advantages are: all-year food production, local need-based production(Sarkar & Majumder 2015), reduced transport needs and reduced food waste associated with transportation (Garg & Balodi 2014; Sarkar & Majumder 2015). Furthermore, it has been found that vertical farms have a much higher crop yield, decreased water usage, less disease transmission – less pesticides, pests, deforestation (Garg & Balodi 2014; Sarkar & Majumder 2015). Published research also claims that VF provide a paradigm shift in terms of agricultural behaviour, i.e. it supports the concept of intensified instead of extensified agriculture. For example, 1 indoor acre is equal to 3 outdoor acres of strawberries according to (Banerjee & Adenaeuer 2014). Additionally, VF allows the reuse of buildings (Garg & Balodi 2014; Banerjee & Adenaeuer 2014), encourages coupling of food production (food + fish, i.e. Tilapia) (Banerjee & Adenaeuer 2014). Depending on the type of

VF, most designs do not require heavy agricultural machinery or inorganic fertilisers and it helps to reduce transport pollution (Garg & Balodi 2014). Further benefits are: help to create sustainable urban centres, purifying air and positive psychological effect. Moreover, the vertical farm concept could provide solution for extreme situations such as growing food in space, poles and refugee camps (Banerjee & Adenaeuer 2014). Currently, some of the most profitable and common crops are: green leafy vegetables, cabbage, lettuce, basil, tomatoes, okra, cantaloupe, bell peppers and roses (Sarkar & Majumder 2015).

Latest research analysing various types of cultivation of edible plants on buildings also shed some light in terms of the benefits and limitations of soil-less and soil-based agriculture (Samangooei et al, 2016). Their investigation assessed a number of case studies under a scoring system using these parameters: Environmental, Social and Economic impact. Such study revealed that soil-less systems (such as hydroponic vertical farms) are more productive per square metre. However, soil-based systems are more affordable and are more likely to be more environmentally and socially beneficial overall. Nevertheless, (Samangooei et al. 2016) admit to be only at the beginning of a larger exploration of the two types of cultivation systems (i.e. soil-less and soil-based).

## **Discussion**

Various academic papers stated that the best design for a vertical farm has not yet been found (Sarkar & Majumder 2015; Banerjee & Adenaeuer 2014; Fischetti 2008; Al-Chalabi 2015). Some suggested that one of the best options might be based on the pyramid farm recommended by Eric Ellingsen and Dr. Despommier (Sarkar & Majumder 2015; Ellingsen & Despommier 2008), but this design is still relatively futuristic and it can be perceived as an utopia. The economic and environmental feasibility of a true architectural integration of vertical farms requires further in-depth scientific investigation. Furthermore, the literature also highlights the need to design more efficient systems to handle the energy usage on artificial lighting, heating and cooling (Banerjee & Adenaeuer 2014; Kozai et al. 2016). Some academics also agreed on the need to develop research projects that will quantify and qualify the validity of VF (Al-Chalabi 2015; Banerjee & Adenaeuer 2014). Al-Chalabi, from Oxford University, and various other researchers, stated that there is a strong need for a *real pilot* project to test the true integration of VF, this is supported by other published work (Al-Chalabi 2015; Garg & Balodi 2014).

This preliminary literature review provides strong evidence on a number of problems faced by the development of VF. It can be argued that, despite of the various existing vertical farm developments around the world, this is an area that is still in its infancy. This is particularly noticeable due to the weak finances behind most projects of this nature: "According to a survey in February 2014 by the Ministry of Agriculture, Forestry, and Fishery of Japan, among 165 PFALs [Plant Factories with Artificial (or electrical) Lighting], only 25% made a profit, 50% broke even, and 25% lost money" (Kozai et al. 2016).

Based on the literature review, this research project argues that most of the disadvantages behind VF are due to the lack of true integration between VF and urban architecture. Better planning and a cohesive design response could potentially help towards improving the finances and true viability of these concepts.

## **Conclusion**

As it has been shown above, thorough studies and experiments in the area of urban greening and vertical farms have taken place in a number of research projects around the

world (Alexandri & Jones, 2008; Banerjee & Adenaeuer, 2014; Koyama et al, 2013; Pérez et al, 2014). However, despite all the advances and research undertaken to evaluate the integration of green elements, urban crops and vertical farms in cities, less sustainable practices are predominant. It is evident that more research is required to make their integration a reality (Breuste et al. 2013a). Likewise, there is a significant amount of evidence that highlights the need to develop further research in the area of architectural sustainability with the integration of plants (Breuste et al., 2013a; Centre for Sustainable Energy, 2015; Yang et al, 2015). Especially considering the statistics and research showing that vertical farms (or plant factories) are not particularly strong financially (Kozai et al. 2016), this represents a significant challenge in order to truly achieve the integration of VF within cities.

This paper is the first step of a larger research work. The author aimed to present a brief review on the historic development of vertical farms and the current state of research in this area. This is followed by suggesting and establishing a sensible and informed pathway towards the future direction of the research in the area of urban vertical farms. After identifying the initial gaps that exist in this area, as it was described in the previous sections, the next phase of this research aims to layout a number of VF site visits in various locations. Simultaneously, experimental fieldwork will be undertaken in order to optimise the practises followed by currently active vertical farms, thereafter suggesting improved integration within the built environment. This will be assisted by computer simulation and data analysis in order to provide documented evidence of the followed procedure. The final goal is to provide sound and evidenced academic research in the area of vertical farms integrated into the built environment.

## Acknowledgments

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## References

- Al-Chalabi, M., 2015. Vertical farming: Skyscraper sustainability? *Sustainable Cities and Society*, 18, pp.74–77.
- Alexandri, E. & Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, 43(4), pp.480–493.
- Association for Vertical Farming, 2016. AVF Map. Available at: <https://vertical-farming.net/>.
- Bailey, G.E., 1915. *Vertical Farming*, California: E. I. Du Pont de Nemours Powder Co. Wilmington, Delaware.
- Banerjee, C. & Adenaeuer, L., 2014. Up, Up and Away! The Economics of Vertical Farming. *Journal of Agricultural Studies*, 2(1), p.40.
- Besthorn, F.H., 2013. Vertical Farming: Social Work and Sustainable Urban Agriculture in an Age of Global Food Crises. *Australian Social Work*, 66(2), pp.187–203.
- Breuste, J., Qureshi, S. & Li, J., 2013a. Applied urban ecology for sustainable urban environment. *Urban Ecosystems*, 16(4), pp.675–680.
- Breuste, J., Qureshi, S. & Li, J., 2013b. Scaling down the ecosystem services at local level for urban parks of three megacities. *Hercynia N.F.*, 46(October), pp.1–20.
- Centre for Sustainable Energy, 2015. *Low Carbon Neighbourhood Planning A guidebook*, Bristol.
- Despommier, D., 2009. The Rise of Vertical Farms. *Scientific American*, pp.80–87.
- Despommier, D., 2010. *The Vertical Farm*, USA: Picador.
- Despommier, D., 2013. The Vertical Farm: A Keystone Concept for the the Ecocity - TED Talk x Warwick. Available at: <https://www.youtube.com/watch?v=mwaZc7B8Hnc>.

- Dr Dickson Despommier, 2013. TED Talk x Warwick.
- El-Zeiny, R.M.A., 2012. Biomimicry as a Problem Solving Methodology in Interior Architecture. *Procedia - Social and Behavioral Sciences*, 50(July), pp.502–512.
- Ellingsen, E. & Despommier, D., 2008. The Vertical Farm - The origin of a 21st century architectural typology. *CTBUH Journal*.
- Fischetti, M., 2008. Growing Vertical: Skyscraper Farming. *Scientific American*, pp.74–79.
- Garg, A. & Balodi, R., 2014. Recent Trends in Agriculture: Vertical Farming and Organic Farming. *Advances in Plants & Agriculture Research*, 1(4).
- Hasse, J.E. & Lathrop, R.G., 2003. Land resource impact indicators of urban sprawl. *Applied Geography*, 23(2–3), pp.159–175.
- Holland Hydroponics & Horticulture, Holland Hydroponics & Horticulture. Available at: <http://www.hydroponics.co.uk/> [Accessed September 8, 2016].
- Johnson, M.P., 2001. Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda. *Environment and Planning A*, 33(4), pp.717–735.
- Koyama, T. et al., 2013. Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. *Building and Environment*, 66, pp.96–103.
- Kozai, T., Niu, G. & Takagaki, M., 2016. *Plant Factory An Indoor Vertical Farming System for Efficient Quality Food Production*, Academic Press, Elsevier.
- Lurie-Luke, E., 2014. Product and technology innovation: what can biomimicry inspire? *Biotechnology advances*, 32(8), pp.1494–505.
- Pawlyn, M., 2011. *Biomimicry in Architecture*, London: RIBA Publishing.
- Pérez, G. et al., 2014. Vertical Greenery Systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews*, 39, pp.139–165.
- pH Hydro, 2014. Powerhouse Hydroponics. Available at: <http://www.powerhousehydroponics.com/aeroponics-101-facts-about-soilless-growing-technology/> [Accessed September 8, 2016].
- Plan 2B Green, 2011. Vertical Farming. Vertical Farm History. Available at: <http://www3.jjc.edu/ftp/wdc12/jjurkiewicz/history.html>.
- Safikhani, T. et al., 2014. A review of energy characteristic of vertical greenery systems. *Renewable and Sustainable Energy Reviews*, 40, pp.450–462.
- Samangooei, M., Sassi, P. & Lack, A., 2016. Soil-less systems vs. soil-based systems for cultivating edible plants on buildings in relation to the contribution towards sustainable cities. *Future of Food: Journal on Food, Agriculture and Society*, 4(2), pp.24–39.
- Sarkar, A. & Majumder, M., 2015. Opportunities and Challenges in sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies*, 2(2), pp.98–105.
- The Aquaponic Source 2017, 2017. The Aquaponic Source. Available at: <https://www.theaquaponicsource.com/what-is-aquaponics/> [Accessed September 8, 2016].
- Yang, Q., 2014. Prophase exploration on technologies of vertical farming and urban agriculture in China, Available at: <http://vfua.org/wp-content/uploads/2014/12/Qichang-Yang.pdf>.



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*Design to Thrive*

## Urban micro-climate change evaluation and mitigation solutions—a case from Xi'an, China

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**Abstract:** The effects of urban climate change have drawn attention to monitoring and evaluating outdoor environment in cities worldwide. Especially in China, rapid, large-scale urban development alongside rapid economic growth has resulted in considerable urban climate change since the 1990s, creating urban environmental problems such as haze. Currently, most of the studies on this matter that are being conducted in China focus on the impact of urban development on urban climate change. Few studies have focused on developing solutions for microscale urban climate change. In this study, four micro-scaled districts in Xi'an were selected to represent the typical building styles that developed in different historical periods. These are a traditional residential district (1950s), a low-rise district (1980s), a mixed-rise district (1970s-2000s), and a high-rise district (2010s). The urban climate was here evaluated using the urban environmental simulation system scSTREAM, and the mitigation solutions of urban typology optimizing are proposed in the discussion. The change in the urban micro-climate along with the change in urban typology were indicated, and the proposed solutions indicate in detail the impact of various solutions on different urban conditions. This may which could provide hints for urban climate change mitigation and sustainable urban planning in the future.

**Keywords:** Urban climate change, Environmental simulation, Urban typology, Air pollution

### Introduction

The effects of urban climate change have drawn attention to monitoring and evaluating outdoor thermal comfort in cities worldwide. Especially in China, rapid, large-scale urban development alongside rapid economic growth has resulted in considerable urban climate change since the 1990s, creating urban environmental problems such as haze. The use of primary energy makes up the main constituent of Chinese haze, and the high-density urban typology accelerates the aggregation of air pollution in the urban areas. An “urban air path” is here proposed as a means of optimizing the urban wind pattern and increasing wind speed inside cities from the view of urban planning (Werner, 1979; Ren et al., 2014). Recently, the use of urban wind corridors has become widely discussed (Memon et al., 2013), especially in many Chinese cities such as Beijing (Du et al., 2016), Shanghai (Shi et al., 2016), Guangzhou (Liang et al., 2014), Changsha (Xi et al., 2010), Nanjing (Weng et al., 2015), Wuhan (Li et al., 2014), Zhengzhou (Bai, 2015), and the Pearl River Delta (Ren et al., 2016). Most of the studies on this matter that are being conducted in China focus on the impact of urban development

on urban climate change or on mapping the urban wind corridor on a large scale. Few studies have focused on developing solutions for microscale urban climate change.

Xi'an is located in the middle of China, geographically. With the extremely fast urban development that took place in China after the 1970s, Xi'an had tripled in geographic area by 2010, and the building density increased dramatically. Meanwhile, the annual average air temperature has increased about 3°C in the past 50 years. In 2012, the Xi'an Meteorological Administration reported that 70% of the days in autumn and winter were haze weather days. For this reason, urban climate change mitigation has become an urgent issue in Xi'an.

In this study, four micro-scaled districts in Xi'an were selected to represent the typical building styles that developed in different historical periods. These are a traditional residential district (1950s), a low-rise district (1980s), a mixed-rise district (1970s–2000s), and a high-rise district (2010s). The urban climate was here evaluated using the commercial urban environmental simulation system scSTREAM, and the mitigation solutions of urban typology optimizing are proposed in the discussion. The comparison and discussion among the four selected districts indicated the changes in the urban micro-climate along with the changes in urban typology, and the proposed solutions indicate in detail the impact of various solutions on different urban conditions. This may provide hints for urban climate change mitigation and sustainable urban planning in the future.

## Methodology

### *Field Measurements*

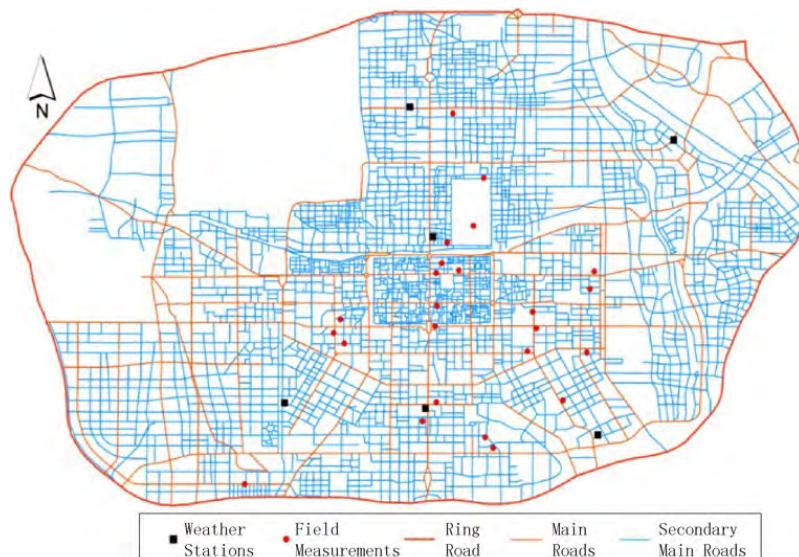


Figure 1. The location distribution of field measurements in Xi'an city

The field measurements were carried out between June 11 and August 27, 2016 in 24 locations in Xi'an City, and 3 days of measurements were taken at each location. The normalization statistical method was used to normalize the weather conditions measured on different days, and Kriging was used for spatial unification (Krige, 1951). The concentration of PM<sub>10</sub> was measured at these points in order to assess the distribution of air pollution in urban area.

## Selected Urban Areas

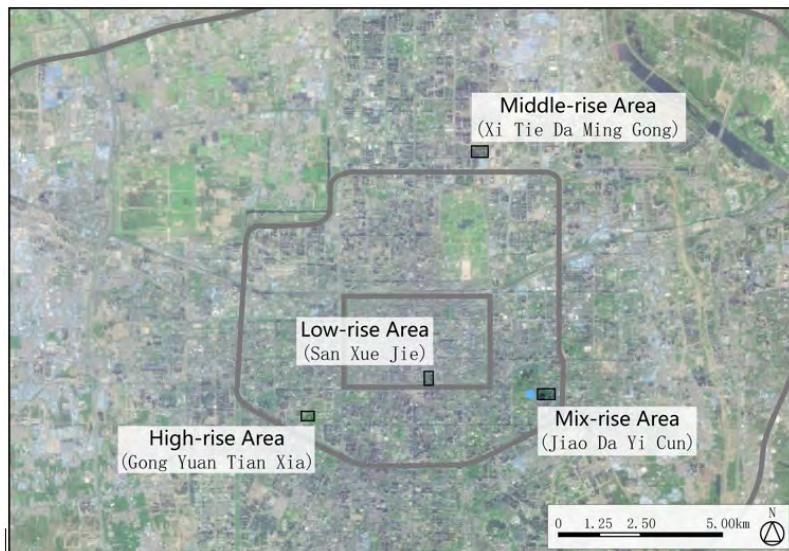


Figure 2. Xi'an satellite photo with the four areas selected for this study, and defined as low-rise area (Sanxuejie), middle-rise area (Xitedaminggong), mix-rise area (Jiaodayicun) and high-rise area (Gongyuantianxia). The area represented in this figure is indicated in Figure 3 and Table 1.

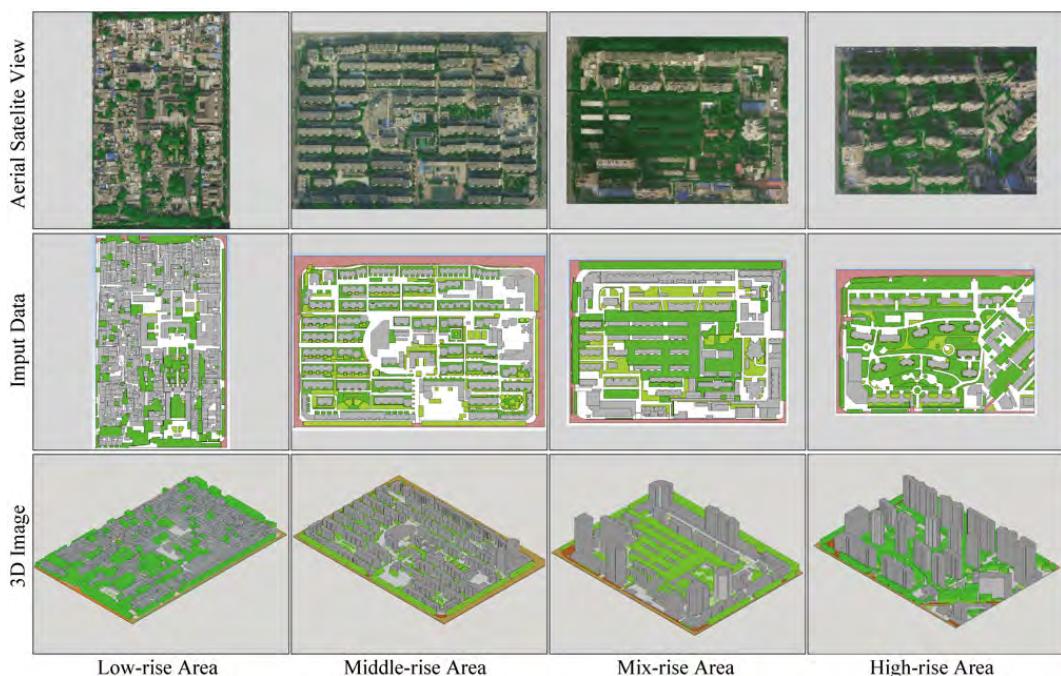


Figure 3. Image selected areas and simulation domain data.

Four typical residential areas were selected for simulation and discussion. The first, Sanxuejie, is a low-rise area, a traditional residential zone rebuilt after the 1950s. It retains the urban form used in China since the Ming and Qing Dynasties (about 600 years ago), with narrow streets between residential buildings, most of which have 2 floors. The second area, Xitedaminggong, is a middle-rise neighborhood developed in the early 1990s. All of the residential buildings are 5 floors in height and perfectly represent the character of the building type constructed in the period between 1979 to the beginning of 1990s. The third neighborhood, Jiaodayicun, is a mix-rise area of low-rise and high-rise buildings, home to a variety of building styles developed around the 1980s and 2000s. The last selected

neighborhood, Gongyuantianxia, is a high-rise residential neighborhood developed in 2009. The average building floor in this area was 17 floors in height, representing the common development style after 2000.

### ***Urban Environmental Simulation***

A commercial CFD code, scSTREAM (Software Cradle Co., 2011), was used to simulate the urban ventilation properties. Detailed distributions of air current and pressure per direction can be visualized. The simulation models were built according to the realities shown in Figure 3, and the detailed input data are presented in Tables 1, 2, and 3.

Table 1. Details of simulation domain size in the four selected areas.

	Low-rise	Middle-rise	Mix-rise	High-rise
Site Size (m)	280*440	520*364	450*340	410*300
Simulation Size (m)	1080*1240	1520*1364	1450*1340	1410*1300
Grid Size (m)	0.6-6.0			

Table 2. Land use and building height properties in the four selected areas.

	Low-rise	Middle-rise	Mix-rise	High-rise
Site Area ( $m^2$ )	123200	189280	153000	95850
Built Area (%)	51	19	14	6
Green Area (%)	22	28	41	49
Floor Area (%)	106	153	242	254
Average Floor	2	5	7	17

Table 3. Details of ground surface material characteristics for simulation.

	Materials	Density [kg/m <sup>3</sup> ]	Specific heat [J/(kg·K)]	Thermal conductivity [W/(m·K)]
Building	Concrete	1600	1000	0.65
Road	Asphalt	2120	920	0.74
Side Walk	Redbrick	1650	840	0.62
Inside surface	Mortar	2000	800	1.3
Green	Soil	1340	1700	0.7

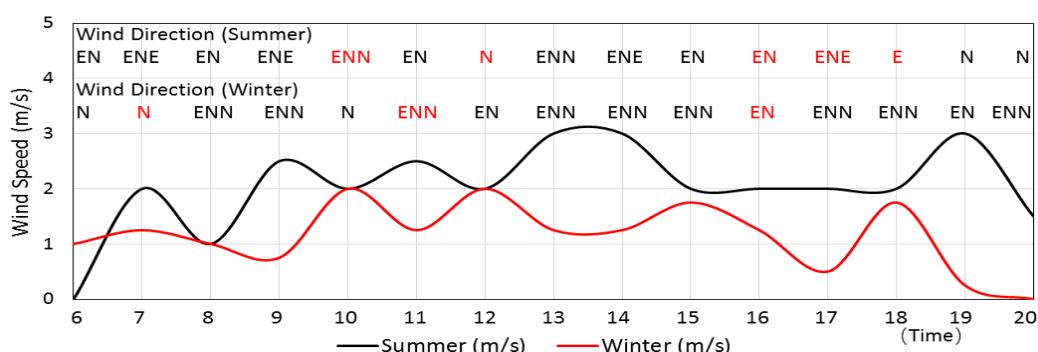


Figure 4. The wind condition in a typical summer day (July 21, 2016) and a typical winter day (December 21, 2015). The main wind directions are shown in red colour.

The wind environment (Xi'an Weather Station, 2016) on a typical summer day (July 21, 2016) and a typical winter day (December 21, 2015) were selected for analysis. The wind direction and wind speed between 6:00 a.m. and 8:00 p.m. are shown in Figure 4. The average wind speed on the summer day was 2 m/s, and the wind directions were N, ENN, EN, ENE, and E, the main being EN; the average wind speed on the winter day was 1.25 m/s, and the wind directions were N, ENN, and EN, the main direction being ENN. The average wind speed and all of the wind directions in different seasons served as the initial condition for the simulations in scSTREAM. The main wind directions were here used for detailed results analysis and discussion.

## Results

### *Air pollution distribution in Xi'an city*

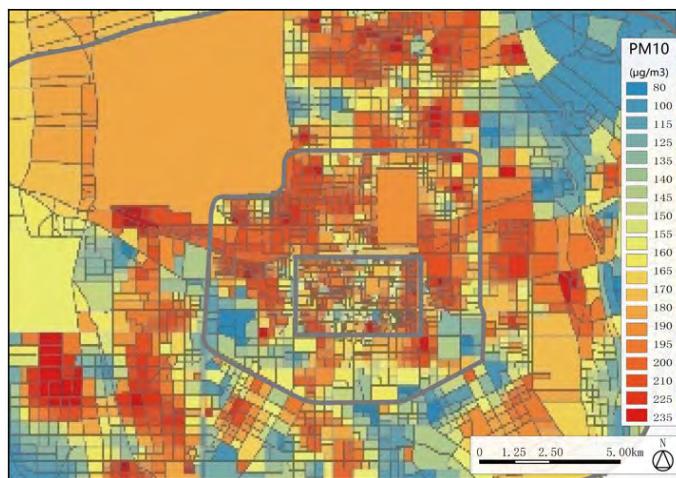


Figure 5. Distribution of PM<sub>10</sub> concentration in the central of Xi'an.

The field measurement results of the PM<sub>10</sub> concentration distribution in the summer of 2016 are shown in Figure 5. The air pollution was found not to be uniformly distributed all over the city. Comparison of Figure 5 and the satellite photo in Figure 2 showed the distribution of air pollution to be partially but directly related to urban density. This is because the urban typology affects urban ventilation and accelerates aggregation, and the air pollution in high density urban districts is subsequently high.

In order to clarify the mechanism of the air pollution concentration in high density areas, the low-rise and middle-rise areas that located in highly polluted areas are selected for simulation. This phenomenon will be discussed with the simulation results.

### *Wind Environment Simulation*

On a summer day, 5 wind directions (N, ENN, EN, ENE, E) were simulated at a wind speed of 2 m/s. On a winter day, 3 wind directions (N, ENN, EN) were simulated at a wind speed of 1.25 m/s are simulated. Figure 6 and 7 present the simulation results in the selected 4 urban areas.

In summer (Figure 6), with the effects from trees, the median wind speed in the low-rise area was slower than in the other areas, and the wind speed in the mix-rise area was fastest. With a wind direction of EN, the median wind speed in mix-rise area was 0.35 m/s, which was 0.15 m/s higher than in the low-rise and middle-rise areas, respectively. The median wind speed in high-rise area was slightly slower (0.03–0.06 m/s) than in the low-rise and middle-rise areas, but there were small areas of higher wind speed in the high-rise area,

and these reached 2.13 m/s (2–3 times of the max wind speed in the low-rise and middle-rise areas). This could explain the results of high PM<sub>10</sub> concentration measured in low-rise and middle-rise areas shown in Figure 5.

In winter (Figure 7), without the effects from trees, the median wind speed in the mixed-rise area was higher than in the other areas. With a wind direction of ENN, the median wind speed in mixed-rise area was 0.24m/s higher than in the low-rise area, and 0.19m/s higher than in the middle-rise area. The median wind speed in the high-rise area is 0.09 and 0.28m/s lower than in the middle-rise and mixed-rise areas. This is to say, the low-rise area (high built density) and the high-rise area (high urban roughness) are reducing the urban wind speed.

In most of the cases, wind direction of EN provides the highest wind speed in all over the area. But the results of high-rise area in summer is lower than the other directions. This is because of the effects from trees.

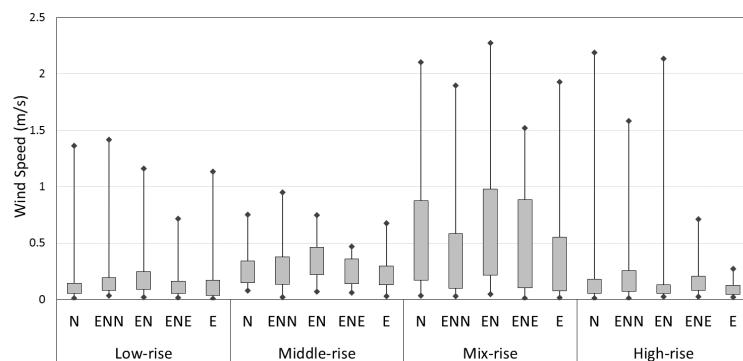


Figure 6. Wind speed in four selected areas in a typical summer day (July 21, 2016).

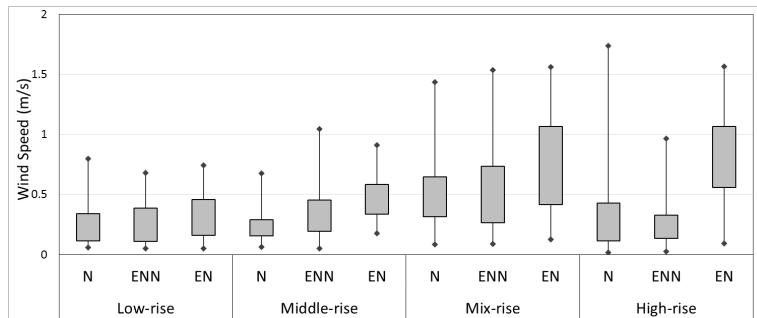


Figure 7. Wind speed in four selected areas in a typical winter day (December 21, 2015).

### **Wind Speed Distribution**

Figures 8 and 9 show the details of wind speed distribution inside these four areas in the summer and winter. In the low-rise area, because of the high building density and narrow corridors between buildings, the overall wind speed was low, and it also had a pronounced effect on downwind areas. In the high-rise area, some areas of high wind speed were observed in between the high-rise buildings, but the wind speed in the leeside of the big volume buildings was extremely low. The mix-rise area showed the best ventilation properties of the four areas. Therefore, the traditional urban typology with low density and high built coverage creates the low urban ventilation at the human level. Meanwhile, high-rise districts with large open space inside of the district also reduces the overall wind speed.

In winter, without the effects from the trees, higher ventilation could be observed inside of the four districts. Especially in the high-rise district, the wind property inside of the community is promoted in the winter.

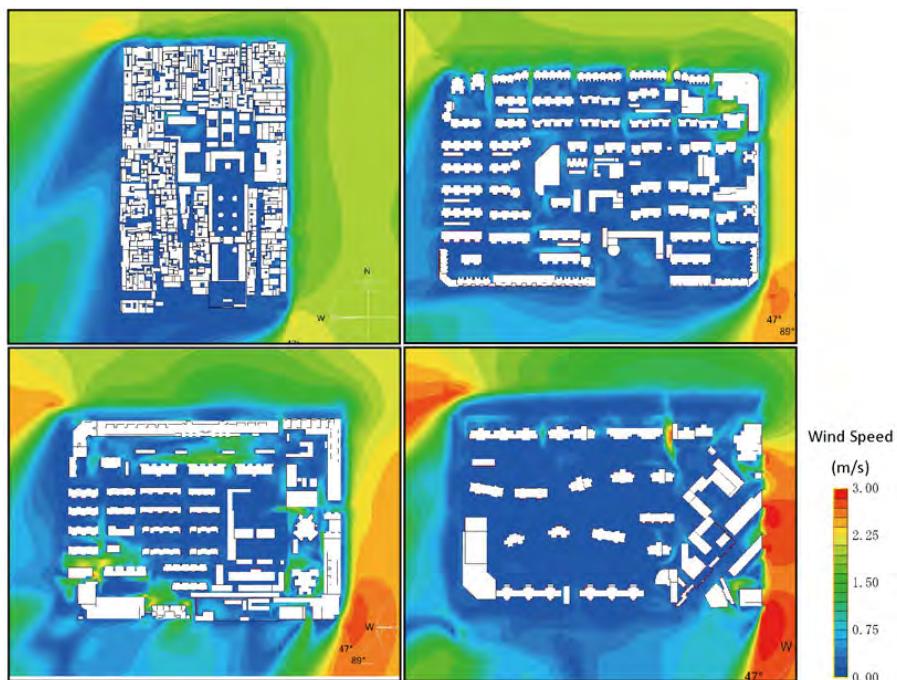


Figure 8. Wind speed distribution in four selected areas at 1.5m height from the ground in summer (wind speed: 2m/s; wind direction: EN).

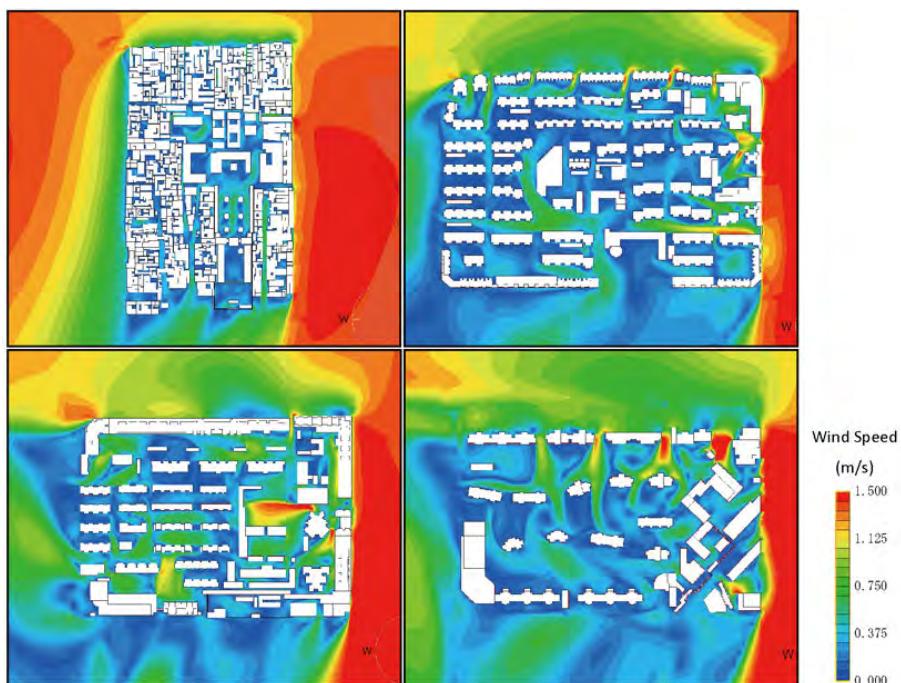


Figure 9. Wind speed distribution in four selected areas at 1.5m height from the ground in winter (wind speed: 1.25m/s; wind direction: ENN).

## Discussion

Urban ventilation plays an important role in the urban environment. In summer, urban ventilation contributes to urban heat dissipation and urban heat island mitigation. In winter, high wind speed accelerates the aggregation of air pollution. Results demonstrated that the urban typology affects urban ventilation and urban air quality. However, it is usually difficult to change the urban form over a short period in areas that have already been developed.

Most of China's cities have undergone fast economic growth, urban expansion, and urban redevelopment. This unique situation is the reason of the rapid environmental degradation in Chinese cities, which could also be useful to the other countries. In the meantime, the fast change in form in China's urban areas has provided an opportunity to optimize urban environments in short periods. This requires an urgent establishment of related policies to regularize environmental urban development and redevelopment.

## Conclusion

This work demonstrated that the wind environment in the low-rise area and the high-rise area are characterized by high building density and the pronounced urban roughness. Wind speed was 0.04 to 0.09 m/s lower in the high-rise area than in the middle-rise area and 0.04 to 0.14 m/s lower in the low-rise area than in the middle-rise area. Wind speed is 0.19 to 0.27 m/s lower in the high-rise area than in the mixed-rise area and 0.21 to 0.28 m/s lower in the low-rise area than in the mixed-rise area. Overall, the balance between building height and building ratio should be considered in future urban development projects. The information from this work provides information useful to the cultivation of environmental urban policy.

## Acknowledgements

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## References

- Bai X. (2015). *Luoyang City Air Corridor Planning Management Research – In the Perspective of Haze Weather Governance*. Master. Zhengzhou University
- Du W., Fang X., Liu Y., He Y., He J. (2016). Construction of Ventilation Corridors in the Beijing Central Urban Area Based on Meteorology and GIS Technology. *Urban Planning Forum*, 2016, (5): 79-85
- Krige, Danie G. (1951). A statistical approach to some basic mine valuation problems on the Witwatersrand. *J. of the Chem., Metal. and Mining Soc. of South Africa*. 52 (6): 119–139.
- Liang H., Li X., Xiao R. (2014). Research on the Planning and Control method of Urban Ventilation Corridors A Case Study of Regulatory Planning of Baiyun New Town, Guangzhou. *Landscape Architecture*, 2014, (5): 92-96
- Li J., Rong Y. (2014). Urban Design Control For Wind Corridor: Wuhan Case[J]. *Planners*, 2014, 08.
- Memon, N., Gryning, Sven E., Khan A., Batchvarova, E. (2013). Wind characteristic in the wind corridor in Southern Pakistan, the effect of the monsoon. *EMS Annual Meeting Abstracts. European Meteorological Society*, 2013. (EMS Annual Meeting Abstracts, Vol. 10)
- Ren C., Yuan C., Kwan H C, et al. (2014). A Study of Air Path and Its Application in Urban Planning[J]. *Urban Planning Forum*, 2014, 161(9):H529-H538
- Ren Q., Wei J., Dai W. (2016). Characteristics of Regional Wind Environment and Construction of Ventilation Corridors : A Case Study of the Pearl River Delta. *Tropical Geography*, 2016, 36(5)
- Shi J., Zhen M. (2016). Sustainable Development of Large Cities Facing Climate Change – Taking Shanghai as an Example[J]. *Resources and Environment in the Yangtze Basin*, 2016, 25(1): P468
- Software Cradle Co., Osaka 530-0001 Japan 2011 scSTREAM. *Thermo-fluid Analysis System with Structured Mesh Generator*
- Weng Q., Zhang H., Bao H., Liu J., Wu H. (2015). Study on Ventilation Channels of Nanjing City. *Science Technology and Engineering*, 2015, 15(11): 89-94
- Werner G. (1979). Regionale Luftaustauschprozesse und ihre Bedeutung fur die raumliche Planung[J]. *Landschaft Und Stadt*, 1979
- Xi'an Weather Station. (2016). [www.rp5.ru](http://www.rp5.ru). (Accessed on Feb. 20, 2017)
- Xi H., Jiao S., Lu L. (2010). Research on the Mode of Creating Urban Natural Ventilation Channel for the Areas where It's Hot in Summer and Cool in Winter: Take Changsha as an Example. *Huazhong Architecture*, 2010, 28(6): 106-107



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## Progressive building energy criteria modification in response to future climate change

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**Abstract:** Annual building energy consumption is dominated by cooling energy in subtropical Taiwan. While cooling energy is closely influenced by outdoor meteorological condition, the global warming effect would affect the change of cooling energy in the future Taiwan. To constrain excessive cooling energy consumption in the future, the cooling energy rise due to climate change should be neutralized and the building regulation criteria should be progressively modified over years in accordance with the future climate. This study tried to investigate building energy performance based on building regulation criteria in Taiwan to understand the cooling energy variation in the future climate. A design of experiments using structured orthogonal array method is adopted for case generation and for studying the synthesis effect of several envelope design strategies. Each generated case was simulated by EnergyPlus against the prepared hourly future climate data encompasses RCP45 and RCP85 scenarios. The results revealed that the cooling energy varying with envelope configuration is hard to remain at current level after 2050s and will increase at least 40% in 2080s. Therefore, we further proposed easily understandable progressive criteria modification schemes that are changed for every 30 years in neutralizing the climate change impact on building cooling energy rise.

**Keywords:** building energy regulation, climate change, criteria adaptation

### Introduction

With the increasing urbanization and relying on electrical power, the research about future climate and energy efficiency are both important in the warming trend especially in hot and humid Taiwan. There are three elements of urban development: infrastructure, building operations, and transportation. A research in the U.S. indicated that the most targeted measures to reduce urban energy usage should focus on building operation (Christopher et al., 2006). In Taiwan, it consumes more than 30% electrical power in essential functions of residential and commercial buildings. Furthermore, there is 40% electricity using in air condition system (Yang and Hwang, 1993, 1995). While the building energy usage is dominated by outdoor climate and building envelope configurations, this study focuses on the energy performance of varying building factors under future climate scenarios.

To understand the climate change impact on building energy, a reach based on the warming scenario predicted by IPCC revealed that a 4.4 °C rise in mean annual air temperature relative to the 1961-1990 period would make the annual cooling energy demand for office buildings increase by 223-1050% in Switzerland (Frank, 2005). In Slovenia, four combinations of temperature and solar radiation change were concerned to predict the future climate and the influences to office buildings (Vidrih and Medved, 2008). The results

showed that the overheat time of office buildings would rise to about 1270 hours per year and that the heating load and cooling load in the future would grow by 12% and 28% respectively compared to those average in 1992 to 2003.

In the UK, Chow *et al.* (Chow and Levermore, 2010) used the UKCIP02 model to predict the climate condition in the future time slices (2020s, 2050s, and 2080s) in UK. They checked the office buildings based on UK Building Regulation and found that the increase of cooling load would be the same as the decrease of the heating load. Additionally, the new office buildings complying with 2002 Building Regulations could just maintain the energy consumption constantly with climate change. Another research in UK (Pan and Garmston, 2012) also found that there are almost one-third of 404 new buildings built in 2006 to 2009 dissatisfied with building regulations. Other research meant to confine the building energy usage by enhancing the building regulations (Kang and Rhee, 2014a, Hamza and Greenwood, 2009) indicated that there are always non-compliance buildings no matter how stringency of building energy efficiency regulations has increased. Generally, the incomprehensible criteria would result in the incompetent regulations. Thus, this study not only means to promote the criteria of building regulations but also means to identify the factors' contribution to building energy consumption over future climate change. The aim of this study is to construct easily understandable regulation criteria for local government or industries in Taiwan.

## Methodology

To investigate the climate change impact on energy consumption of office buildings in Taiwan, this study adopts EnergyPlus simulator with hourly weather data and virtual building cases to simulate the building performance under the future meteorological conditions. Because of the various factors of building envelope configurations, the Taguchi method is adopted to construct virtual building cases and to implement the mathematical analysis. In addition, the factors setting for virtual building cases refer to building energy regulations in Taiwan.

### ***Building energy regulation in Taiwan***

This study introduced the latest version of Taiwan energy conservation regulations for building envelope design which released in 2015 (Taiwan National Architecture Association, 2015) which demands that the U-value of exterior wall ( $U_w$ ) should be lower than  $2.0 \text{ W/m}^2$  and that the U-value of fenestration ( $U_f$ ) and the average shading factor (SF) of window should both vary with the window-to-wall ratios (WWR). These values should be calculated on each aspect of building façades and should comply with the criteria tabulated in Table 1. The calculation of the SF value in regulation is:

$$SF = \frac{\sum f \times SHGC \times A_{win}}{\sum A_{win}} \quad (1)$$

Where SHGC indicates the solar heat gain coefficient of fenestration;  $f$  means the factor of shading overhang;  $A_{win}$  is the window area on each façade.

Table 1 Building regulation criteria in Taiwan

Window-Wall Ratio	>0.5	0.5-0.4	0.4-0.3	0.3-0.2	0.2-0.1	<0.1
<b>Uf</b>	2.70	3.00	3.50	4.70	5.20	6.50
<b>SF</b>	0.10	0.15	0.25	0.35	0.45	0.55
<b>Uw</b>				2.0		

### **Virtual Building Cases and Taguchi method**

According to the regulation mention above, this study considers ten building factors including:

- (a) window-to-wall ratio (WWR),
- (b) U-value of fenestration ( $U_f$ ),
- (c) solar heat gain coefficient of window (SHGC),
- (d) shading overhang,
- (e) U-value of external wall ( $U_w$ ),
- (f) material of external wall, (g) orientation of building,
- (h) shape factor of building plane,
- (i) occupancy, and
- (j) indoor heat dissipation of equipment.

In addition, shading overhang is defined as the depth of shading device over the height of window.

There are ten factors and three levels of each factor in order to understand the building energy consumption that may vary with different insulation level. Since it is too complicated and time-consuming to discuss each combination with all factors, Taguchi method (Kang and Rhee, 2014b) is adopted to solve such a multivariable simulation. Taguchi method is an experimental design technique providing a simple way to reduce the numbers of experiments by setting multilevel factors into a given orthogonal array. The orthogonal array Table L<sub>81</sub> is chosen to fit all factor levels. All levels are put into the array to construct 81 different office building configurations. The factor level settings are listed in Table 2 while the test cases and control cases are established simultaneously. The factor (a) to (f) of control cases are based on ASHRAE 90.1 standard while factor (h) to (j) are set as same as those in corresponding test buildings.

Table 2 Factor levels of virtual building cases

Factor	Parameters	Test case			Control case Level
		Level 1	Level 2	Level 3	
a	WWR	0.1	0.4	0.7	0.4
b	$U_f$ (W/m <sup>2</sup> K)	5	3	1	3.2
c	SHGC	0.8	0.5	0.2	0.2
d	Shading overhang	0	1	2	0
e	$U_w$ (W/m <sup>2</sup> K)	3.5	2	0.5	0.857
f	Material	Metal	Light RC	Heavy RC	Light RC
g	Orientation (degree)	-60	0	60	Average in four direction
h	Shape	1	2	3	
i	Occupancy (person/m <sup>2</sup> )	0.05	0.1	0.15	Same as the corresponding test cases
j	Equipment (W/m <sup>2</sup> )	10	25	40	

### **Future Weather data**

The weather data put into EnergyPlus simulator is required as hourly data, so downscaling the prediction of global circulation model (GCM) is necessary. The hourly future weather data is constructed by morphing method (Belcher et al., 2005, Huang and Chuang, 2014) with the local weather data and GCM data considering two future climate scenarios which are RCP45 and RCP85 defined by IPCC AR5(Stocker et al., 2013). The local weather data is provided by Central Weather Bureau (CWB) in Taiwan. The local site is Taipei and the base period is 1995-2010. The future weather data is obtained from CanESM2.

The morphing method adopts shifting, stretching, and combination of both parts which are shown as Eq. (2) to (4). By this method, we can use the changes predicted by CanESM2 to construct future hourly data that is suitable for Taipei.

$$x = x_0 + \Delta x_m \quad (2)$$

$$x = \alpha_m x_0 \quad (3)$$

$$x = x_0 + \Delta x_m + \alpha_m (x_0 - x_{0,m}) \quad (4)$$

Where  $x$  is the future value of a certain weather variable;  $x_0$  is the local weather variable;  $\Delta x_m$  and  $\alpha_m$  are the monthly linear change and the monthly proportional change between local data and GCM data.

### **Results and discussion**

The building cooling energy consumption is simulated in base period and two future scenarios. The future scenarios are divided into three time slices: 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100). To understand which building factor influences the cooling energy most, ANOVA is introduced to evaluate the significance of all factors.

#### **Factors contribution**

The specific energy ratio is calculated to simplify the energy consumption evaluation. The specific energy ratio ( $r$ ) is defined as the cooling energy consumption of test cases in the future over that of control cases in base period. The calculation is shown as Eq. (5):

$$r = \frac{\text{Cooling energy use under future weather condition}}{\text{Cooling energy use in base period}} \quad (5)$$

The higher  $r$  value indicates the more cooling energy demand under the future condition comparing to the current level. Also, the specific energy ratios are used to implement ANOVA that help us to understand the factors' contribution to cooling energy varying with changing factor levels. Once we define the contribution of each level, we would be able to evaluate and predict cooling energy consumption of more randomly designed office buildings.

ANOVA is carried out by the average specific ratios ( $\bar{r}$ ) in RCP45 and RCP85 separately. The results reveals that there are four influential factors in cooling energy, and the F-test indicates these four factors, which are WWR,  $U_f$ , SHGC, and shading overhang, containing more than 70% contribution of variance in both RCP45 and RCP85. Though, these factors are marked as principal factors which influence the cooling energy usage most. Then, the factor

contribution could be provided as  $\Delta r$ , calculated as Eq. (6), that indicates the effect of certain factor level on the cooling energy use.

$$\Delta r = r_k - \bar{r} \quad (6)$$

Where  $r_k$  means the specific energy ratio of certain factor level. The  $\Delta r$  of principal factors in different time slices of RCP45 and RCP85 are tabulated in the Table 3 and Table 4.

Table 3 Factor contribution results in RCP45

Factors	properties	Factor effect		
		2020s	2050s	2080s
WWR	0.1	-0.0765	-0.0807	-0.0869
	0.4	-0.0005	-0.0001	0.0004
	0.7	0.0770	0.0808	0.0865
$U_f$ (W/m <sup>2</sup> K)	5	-0.0252	-0.0191	-0.0157
	3	-0.0208	-0.0204	-0.0205
	1	0.0461	0.0395	0.0362
SHGC	0.8	0.1343	0.1352	0.1404
	0.5	-0.0076	-0.0076	-0.0078
	0.2	-0.1267	-0.1276	-0.1326
Shading overhang	0	0.0808	0.0799	0.0827
	1	-0.0151	-0.0151	-0.0156
	2	-0.0658	-0.0648	-0.0671

Table 4 Factor contribution results in RCP85

Factors	properties	Factor effect		
		2020s	2050s	2080s
WWR	0.1	-0.0787	-0.0844	-0.0964
	0.4	-0.0003	0.0002	0.0011
	0.7	0.0790	0.0842	0.0953
$U_f$ (W/m <sup>2</sup> K)	5	-0.0232	-0.0135	0.0008
	3	-0.0207	-0.0202	-0.0195
	1	0.0439	0.0337	0.0186
SHGC	0.8	0.1358	0.1367	0.1411
	0.5	-0.0076	-0.0076	-0.0078
	0.2	-0.1283	-0.1291	-0.1332
Shading overhang	0	0.0813	0.0798	0.0795
	1	-0.0152	-0.0153	-0.0158
	2	-0.0660	-0.0645	-0.0637

### New criteria for Taiwan building conservation regulation

This study further summed up the  $\Delta r$  of the principal factors as the energy consumption ratio ( $R_E$ ) in different time slices compared to the base period:

$$R_E = \bar{r} + \Delta r_{WWR} + \Delta r_{U_f} + \Delta r_{SHGC} + \Delta r_{Shading} + error \quad (7)$$

Typically,  $R_E=1$  indicates the cooling energy consumption of certain combination in the future is equal to nowadays level;  $R_E>1$  indicates the higher cooling energy consumption, and  $R_E<1$  indicates the lower one. That is, we should focus on the envelope combinations which  $R_E=1$  if we mean to construct a criteria recommendation that can confine the cooling energy usage.

The  $R_E$  values of RCP45 and RCP85 are plotted in Fig. 1 and Fig. 2 and are divided into three time slices. The  $R_E$  values increase with the higher WWR and SHGC level and decrease with the higher shading level. In both two scenarios, the  $R_E$  values will be higher than one in WWR=0.7 and will drastically increase in SHGC=0.8. The steady increase of the  $R_E$  values over time will make it difficultly to maintain the cooling energy use after 2050s, especially in RCP85. Additionally, the optimal  $U_f$  is not the lowest one because the over insulated building envelope will store too much indoor dissipation heat.

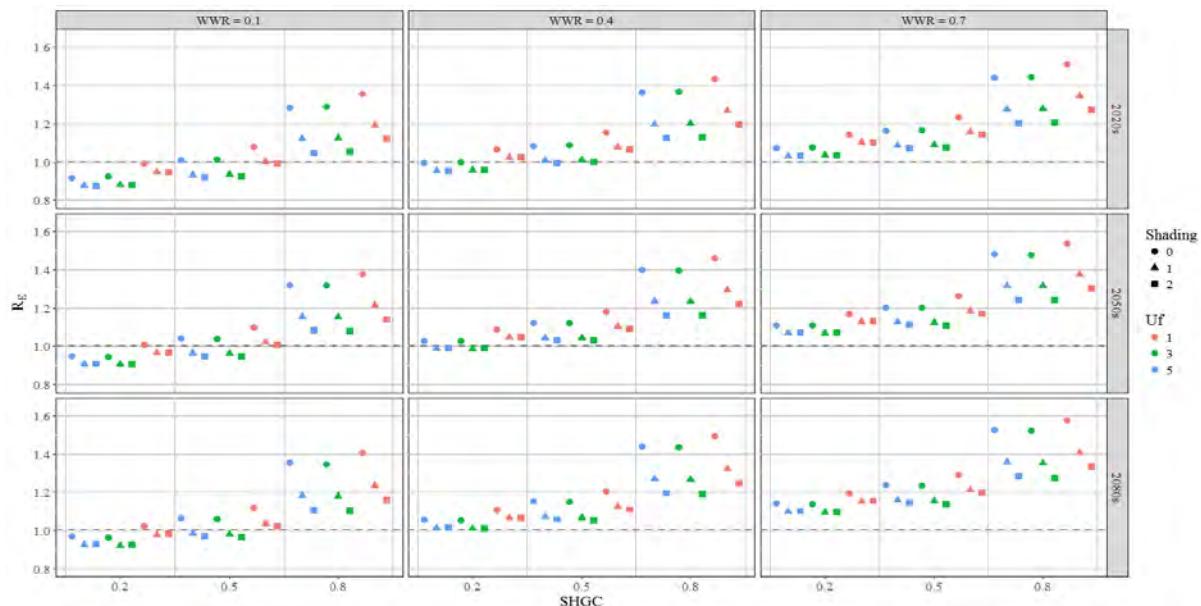


Fig. 1 The  $R_E$  values of top four factors combinations in RCP45

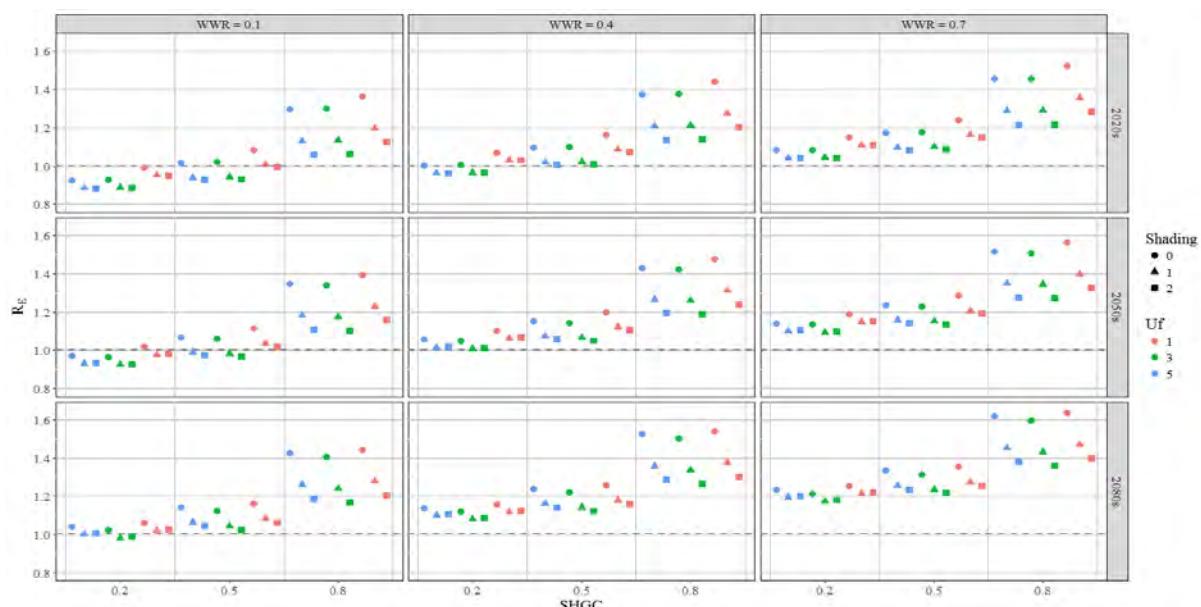


Fig. 2 The  $R_E$  values of top four factors combinations in RCP85

## Conclusion

The office building energy usage in Taiwan is obviously influenced by future climate change. The simulation results match the current building regulation in Taiwan whose major factors are window to wall ratio, shading devices, and the U values of building envelope. The results reveal that cooling energy demand is mainly dominated by the principal factors which are WWR, SHGC,  $U_f$ , and shading overhang. According to the factor contributions, we are able to predict the building energy performance during three future time slices in both RCP45 and RCP85. The increasing cooling energy consumption range varies with different envelope combinations. The worst case in RCP45 and RCP85 would increase 40-60% cooling energy usage in 2080s. On the other hand, the  $R_E$  value would rise when SHGC=0.8 or lack of shading. Moreover, there is no case could maintain the  $R_E$  value in current level when WWR is 0.7 either in RCP45 or in RCP85. That indicates the progress of the building regulation is necessary.

In the meanwhile, this study propose Fig. 1 and Fig. 2 as the criteria recommendation. Through these schemes, it is easily to understand the change of cooling energy use in different building configurations. To maintain the cooling energy usage of office building in Taiwan, we could focus on the cases of which the  $R_E$  values are under or equal to 1 and should make the regulation criteria much stricter over years. The criteria scheme based on the  $R_E$  results is more flexible for Taiwan government and could also provide the measurement over future climate change.

## References

- BELCHER, S. E., HACKER, J. N. & POWELL, D. S. 2005. Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, 26, 49-61.
- CHOW, D. H. C. & LEVERMORE, G. J. 2010. The effects of future climate change on heating and cooling demands in office buildings in the UK. *Building Services Engineering Research and Technology*, 31, 307-323.
- CHRISTOPHER, A. K., JONATHAN, N. & HEATHER, L. M. 2006. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions.
- FRANK, T. 2005. Climate change impacts on building heating and cooling energy demand in Switzerland. *Energy and buildings*, 37, 1175-1185.
- HAMZA, N. & GREENWOOD, D. 2009. Energy conservation regulations: Impacts on design and procurement of low energy buildings. *Building and Environment*, 44, 929-936.
- HUANG, K.-T. & CHUANG, K.-H. 2014. A novel preparation procedure of future weather datasets for building performance simulation. *EGU General Assembly 2014*. Vienna, Austria: European Geosciences Union.
- KANG, H. J. & RHEE, E. K. 2014a. Development of a Sustainable Design Guideline for a School Building in the Early Design Stage. *Journal of Asian Architecture and Building Engineering*, 13, 467-474.
- KANG, H. J. & RHEE, E. K. 2014b. A Development of Heating and Cooling Load Prediction Equations for Office Buildings in Korea. *Journal of Asian Architecture and Building Engineering*, 13, 437-443.
- PAN, W. & GARMSTON, H. 2012. Compliance with building energy regulations for new-build dwellings. *Energy*, 48, 11-22.
- STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M. M. B., K.ALLEN, S., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. 2013. *Climate Change 2013-The Physical Science Basis*. IPCC AR5.
- Taiwan National Architecture Association, (2015). *Design and Technique Directions for Green Building*. Taiwan: Taiwan National Architecture Association.
- VIDRIH, B. & MEDVED, S. 2008. The effects of changes in the climate on the energy demands of buildings. *International Journal of Energy Research*, 32, 1016-1029.
- YANG, K. H. & HWANG, R. L. 1993. The analysis of design strategies on building energy conservation in Taiwan. *Building and Environment*, 28, 429-438.
- YANG, K. H. & HWANG, R. L. 1995. Energy conservation of buildings in Taiwan. *Pattern Recognition*, 28, 1483-1491.

# Aesthetics and Design

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## Towards Advanced Active Façades: Analysis of façade requirements and development of an innovative construction system

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**Abstract:** In Switzerland, as in many European countries, new energy directives focus on decreasing the carbon footprint of buildings by promoting passive and active energy strategies. Among the latter, Building Integrated Photovoltaics (BIPV), which function both as envelope materials and electricity producers, are rapidly becoming more performant. However, their potential remains largely unrealised due to diverse barriers. Architects, in particular, tend to avoid integrating BIPV in their designs because of their limited expressive qualities. In reaction, this on-going research aims at developing design strategies for low-carbon façades while addressing BIPV expressive issues, with the goal of bridging the gap between technology and designers. Within this overall framework, the paper presents the Advanced Active Façade (AAF) concept, which results from analysing the evolution of façade requirements and solutions over time. The AAF simultaneously aims at achieving low embodied energy by benefiting from passive low-carbon design strategies, and generating energy by integrating BIPV technology. The paper introduces the core phase of the research, which consists in the development of the AAF Construction System and AAF Design Strategies. The output of the research will provide architects with a construction system and assessed design strategies to optimize the design process of BIPV façades.

**Keywords:** Building Integrated Photovoltaics (BIPV), Active Façades, Renewable Energy, Construction System, Design Strategies

### Introduction

The European Union is committed to drastically reduce greenhouse gas emissions by 2050: levels should be 80-95% lower when compared to 1990 (Energy Roadmap 2050, 2012). This is why European energy directives are becoming more demanding with regards to performance standards. Switzerland follows the same evolution. Since it decided to gradually withdraw from nuclear power in 2011 (SFOE, 2014), the country undergoes a profound restructuring of its energy system. Its new energy policy establishes that energy consumption from photovoltaic (PV) will represent 20% of the total electricity consumption of the country. Thanks to this energy focus, such technology is becoming more efficient and affordable.

The most innovative offer of PV technology consists in the constructive and architectural integration of PV elements. Building Integrated Photovoltaics (BIPV) have both an architectural function and energy generation capacity.

BIPV permits to reduce material use and initial investment costs when compared to a traditional construction where PV systems are independent and added to the building (Centre Suisse de compétence BIPV, 2015). However, despite this favourable context, BIPV technology is not exploited to the best of its potential. Architects often justify the lack of PV

use in their designs with the limited aesthetics of existing BIPV solutions. As a result, a real gap between technology and architecture exists.

### **Research objectives and methodology**

The on-going doctoral research presented in this paper aims at filling this gap by developing new strategic approaches for the design of active façades. Its ambition is to propose a new prospective basis for façade composition and construction strategies, by fostering the collaboration of product developers, architects and scientists in order to tackle simultaneously architectural, constructive and technological issues.

The work developed in this research focuses on collective residential buildings in the Swiss context. Its long-term objective is to provide pathways for a wide-scale use of BIPV façade solutions in residential buildings and to develop design strategies to improve BIPV's expressive issues. The research methodology (Fig. 1) involves 5 main steps.

Phase 1 consists in an initial analysis of the state of the art of three different fields: 1A) existing façade design strategies in the Swiss context, 1B) constructive evolution of façade's requirements and 1C) BIPV technologies according to their architectural features and requisites.

Phase 2 consists in meeting all trends, requirements and features identified in Phase 1 by designing the Advanced Active Façade (AAF). AAF combines AAF Construction Systems (AAF CS), developed in 2A, and AAF Design Strategies (AAF DS), developed in 2B. The AAF CS meets the most demanding insulating targets and is compatible with a wide range of existing BIPV formats and emerging BIPV technologies. AAF DS are created based on the existing façade strategies (1A), future façade requirements (1B) and BIPV technologies (1C). This guarantees easiness and coherence in the application of the AAF concept to collective residential buildings.

Phase 3 is dedicated to the multi-criteria assessment of the AAF CS and AAF DS in terms of environmental impact, cost, architectural quality and social acceptance. In parallel, to support the technology transfer towards practitioners in the built environment.

Phase 4 is for the construction of a prototype of the AAF CS, which will demonstrate its feasibility.

Phase 5 consists in organising an international student competition around the use of BIPV to validate the approach's applicability for architects in the practice.

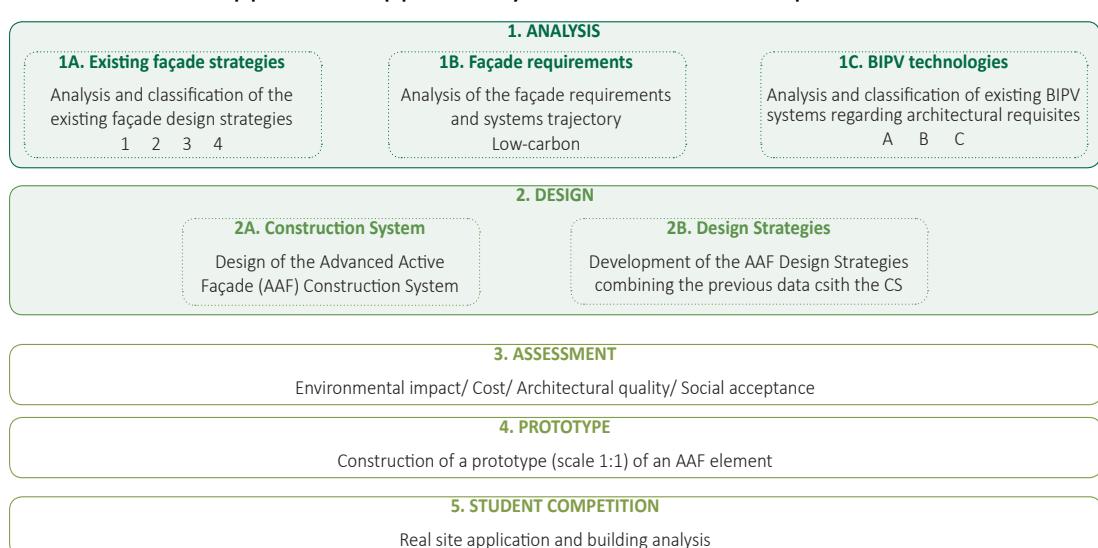


Figure 1. Research Methodology

This paper develops the preliminary results of Phases 1 and 2, i.e. the analysis and the design work packages.

## Preliminary Results

### Phase 1: Analysis

#### *Phase 1A: Analysis and classification of the existing façade design strategies*

While designing a façade, we need to consider the different elements composing it: windows, balconies, doors and solar shading systems (Herzog et al., 2004). The size and modulation of these elements can respect, or not, the pre-existing rhythm established by the building structure: horizontal slabs, beams, pillars and walls. This means that the “face” of the building can allow a direct comprehension of the structure. The façade becomes a skin with an independent expression from the building structure.

We propose a classification based on the dimensional composition of façade materials, elements and building’s general structure in the contemporary Swiss context. The preliminary results provided by this research present a façade composition in four groups (Clua Longas et al., 2016), represented in Figure 2:

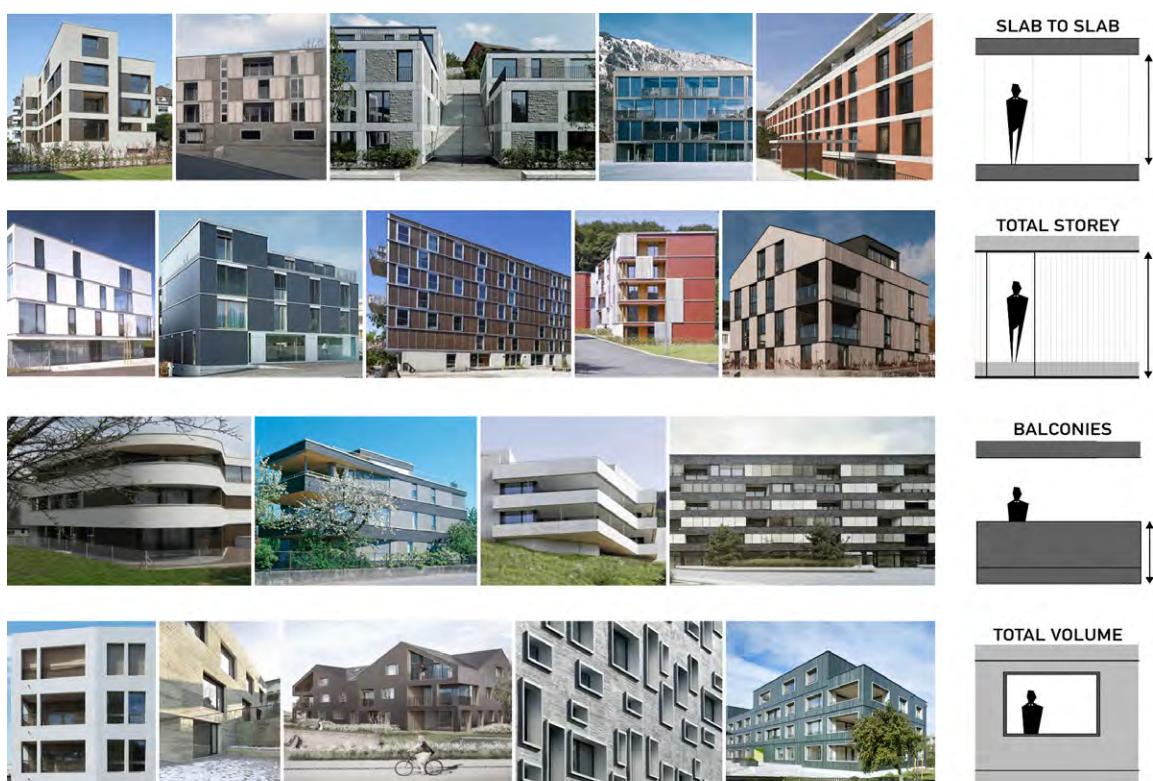


Figure 2. Collective residential buildings’ façade design strategies: classification in four groups

- Strategy 1 ‘Slab to slab’ includes façades where the horizontal slab dimension is apparent and highlighted on the façade.
- Strategy 2 ‘Total storey’ includes façades where the storey structure is also expressed, but the floor slabs are no longer highlighted.
- Strategy 3 ‘Balconies’ refers to facades where balconies are clearly apparent in a large part of the façade.

- Strategy 4 'Total volume' includes façades where the structure rhythm and the interior distribution are not apparent.

Some buildings might present a combination of these four strategies in the same façade or in different ones.

#### *Phase 1B: Analysis of the façade requirements and systems trajectory*

Once the façade composition has been analysed, the façade construction needs to be studied. We have explored the evolution of basic façade systems through history to define the present and near future façade requirements. The goal is to design a façade construction system that meets future needs.

The results of this analysis (Figure 3) indicate that a new objective for façade construction has emerged: achieving a low or zero carbon building. This involves three requirements: i) minimizing the building's energy consumption, ii) lowering its embodied energy and iii) generating energy as part of the envelope solution. Nowadays, there are façades that meet one or two of the mentioned requirements, but very few meet the three of them.

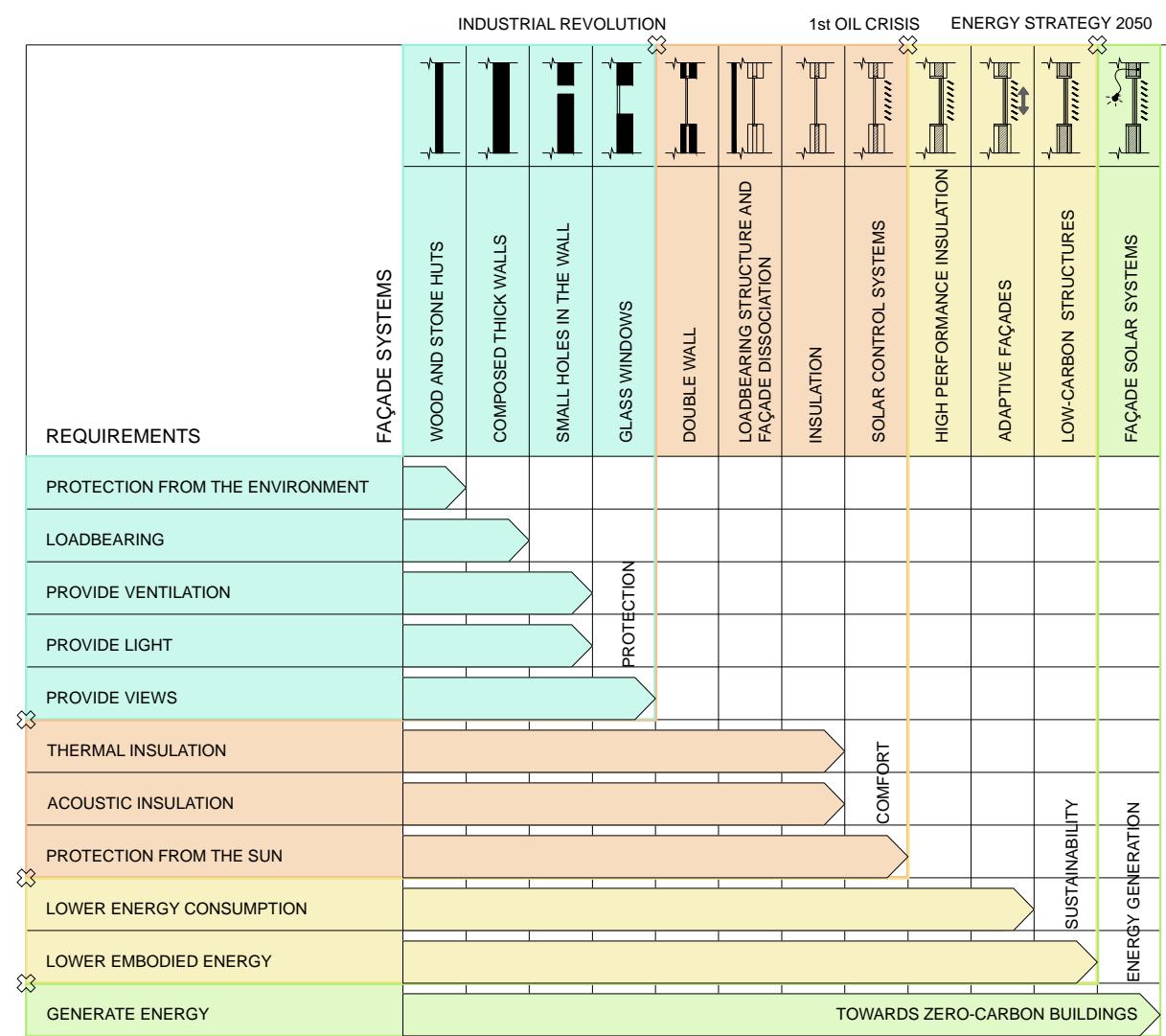


Figure 3. Residential façade requirements and systems trajectory

### *Phase 1C: Analysis and classification of the existing BIPV systems regarding architectural requisites*

There is a growing number of different PV technologies as research is rapidly pushing forward this field (Jelle et al., 2012). PV system's efficiency is greatly improving as science advances. Due to this continuous progress, we will not classify BIPV systems based on PV technology in the framework of this architecture-oriented research. Traditionally, BIPV façade systems have been classified per their technological characteristics. The originality of our approach is that BIPV façade systems are classified per their architectural features given that they play an important role as an integral part of the façade (Roberts and Guariento, 2009).

Therefore, existing systems have been classified, based on their transparency degree, in three groups (Authors, 2016), illustrated in Figure 4: Opaque, Translucent and Transparent. Different technologies such as monocrystalline, polycrystalline or thin-film can fit in one or more of these categories. This classification also welcomes the newest high efficiency modules such as Heterojunction technologies or organic cells, among others.

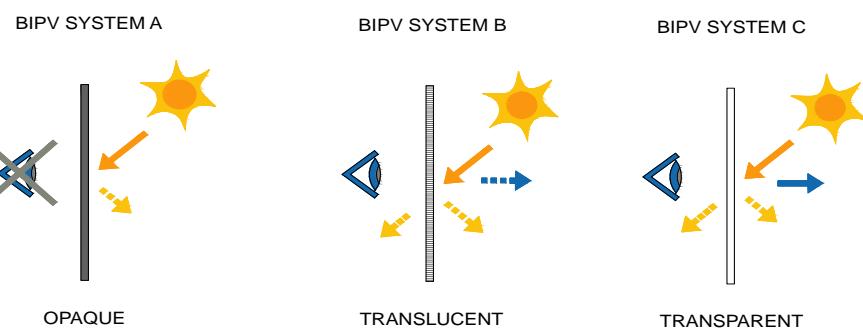


Figure 4. Classification of existing BIPV façade systems, regarding its architectural features

### **Phase 2: Design**

The previous analyses have driven the research to develop the Advanced Active Façade (AAF) concept. Firstly, the AAF design responds to the design trends of today's façade composition. Secondly, it meets the latest façade requirements: it is based on a low-embodied carbon construction, and adapted to the most exigent insulating targets (Minergie P). Thirdly, it is an active element which generates energy thanks to the integration of BIPV systems in its façade composition. The AAF is designed as a non-structural, self-supporting façade, which guarantees more flexibility in its design compared to other loadbearing options. Based on this concept, this research has developed the AAF Construction System (AAF CS) and the AAF Design Strategies (AAF DS).

#### *Phase 2A: Design of the Advanced Active Façade Construction System (AAF CS)*

The AAF CS is a modular construction system that responds to future façade requirements. Its main feature is the combination of passive and active design strategies to lower the building's carbon footprint. The proposed solution consists of a wood-panel based, self-supporting and demountable façade system which meets the most demanding insulating targets and is compatible with a wide range of existing BIPV formats and emerging technologies (Figure 5).

The passive strategy consists of the low-embodied carbon design of the construction system. As seen in the analysis of the façade requirements, energy is one of the most

significant topics in the current debate on façade construction. The embodied carbon of a building accounts for approximately 30% of the total lifetime carbon footprint from the residential building sector (Lane, 2010). More specifically, façades account for 16% of this amount (Cheung and Farnetani, 2015). For this reason, the AAF CS is based on low-carbon construction. This implies the use of local materials (Lupíšek et al., 2015) with low embodied carbon. In the Swiss context, the AAF is designed with a wooden frame (reTHINK WOOD, 2015) filled with cellulose insulation (Gray, 2016). The AAF CS's metallic elements are minimized and, when needed, they are made of recycled aluminium. The use of plywood panels permits the absence of a synthetic vapour barrier as well as a light prefabricated construction. Nothing is adhered, so that components can be easily replaced or disassembled (Kuittinen et al., 2013) for posterior recycling or reuse.

The active strategy consists in integrating a BIPV system in the façade's exterior coating to make it active. This integration implies a previous orientation study of the building to maximize the BIPV performance. An energy-demand simulation is also required to design an active façade which supplies the right percentage of the building's energy needs. The photovoltaic façade's final coating also implies that it has a ventilated construction system, with a 10 cm minimum gap (Brinkworth and Sandberg, 2005, Maturi et al., 2014). Wiring and electrical devices are integrated in the AAF CS façade design to ensure panels' electricity production.

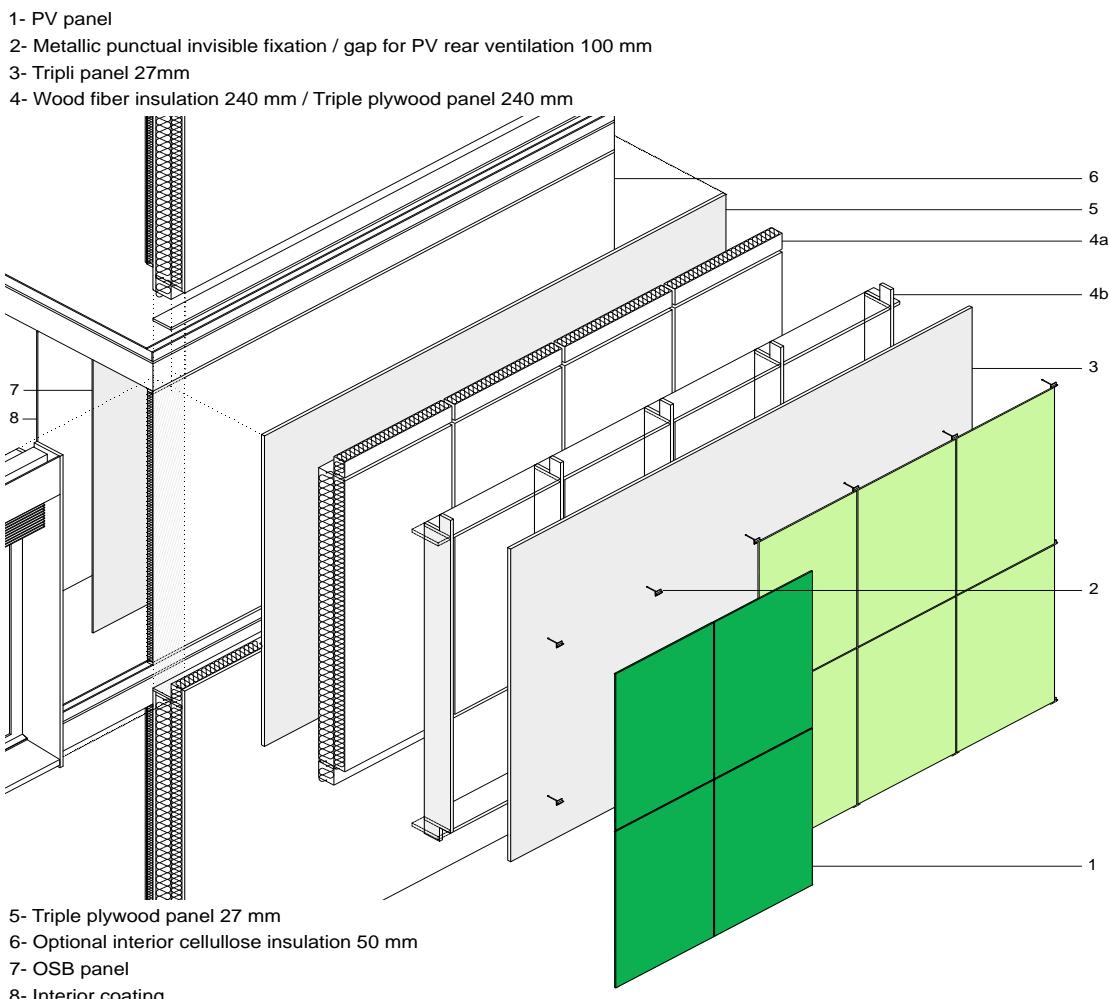


Figure 5. AAF Construction System. Axonometric view of the system composition

The AAF CS, as part of a residential building façade in the Swiss context, also needs to meet other requirements such as comfort and energy regulations, electric directives (LVD 2006/95/EC), security regulations and certification. All these aspects are considered in the AAF CS design.

#### *Phase 2B: Development of the Advanced Active Façade Design Strategies (AAF DS)*

The AAF DS are series of design strategies based on the existing ones (classified in phase 1A) and combined with the three categories of BIPV products (identified in phase 1C). They illustrate different applications of the AAF CS on a real site to validate its capacity to adapt itself to various contexts, architectural requirements and PV technologies. The design process allows the formulation of a series of guidelines for architects to successfully design an Advanced Active Façade. According to recent works (Kylili and Fokaides, 2014), the building orientation which delivers the maximum energy yield for central and southern Europe are the southeast and the southwest façades. This fact will help decide the orientation of a building and the number of AAF to consider to maximize the energy output.

Figure 6 gathers four images which represent the combination of the existing design strategies identified in phase 1A (“Slab to Slab” (1), “Total storey” (2), “Balconies” (3) and “Total Volume” (4)), combined with the three BIPV systems identified in phase 1C (“Opaque”, “Translucent” and “Transparent”). These façade design strategies meet the requirements analysed in phase 1B and can be constructed with the AAF Construction System.



Figure 6. AAF Design Strategies. Combination of different design strategies with different BIPV systems.

## Conclusions

This research aims at filling the gap between technology and architecture in the current practice, demonstrating how BIPV can be considered at the same level as any other construction material. The preliminary conclusions of this on-going research highlight that it is possible to integrate different types of BIPV systems into a prefabricated Advanced Active

Façade Construction System. The latter meets current façade construction requirements and is suitable for residential buildings. The developed work also demonstrates that BIPV can be part of the dimensional composition of a collective residential housing façade. Provided with the Advanced Active Façade Design Strategies, architects are enabled to deal with the expressive and aesthetical aspects of their BIPV designs, producing façades fitting the current composition trends in the Swiss context.

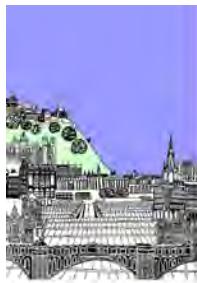
After design issues have been dealt with, the next steps of this on-going research include the detailed multi-criteria assessment of the AAF CS, the construction of a real scale prototype to demonstrate its feasibility and the organization of an international student competition to validate the user-friendliness and convenience of the approach for architects in the practice.

## Acknowledgements

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## References

- Clua Longas, A., Lufkin, S., Rey, E., (2016). Towards a new prospective basis for the design strategies of Active Façades. In: PLEA 2016 Los Angeles - 36th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments.
- Brinkworth, B.J., Sandberg, M. (2005). Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays. *Sol. Energy*.
- Cheung, L., Farnetani, M. (2015). Whole-life carbon: Façades. *Building*.
- Gray, J. (2016). Insulation Materials [online Document]. Sustain. Build. <http://www.sustainablebuild.co.uk/insulationmaterials.html> (accessed 8.12.16).
- Herzog, T., Krippner, R., Lang, W. (2004). Facade Construction Manual. Birkhäuser.
- Jelle, B.P., Breivik, C., Røkenes, H.D. (2012). Building integrated photovoltaic products: A state-of-the-art review and future research opportunities.
- Kuittinen, M., Ludvig, A., Weiss, G., Arvidsson, J., De Angelis, E., Dodoo, A., Dolezal, F., Gustavsson, L., Hafner, A., Häkkinen, T., Linkosalmi, L., Mair am Tinkhof, O., Mötzl, H., Mundt-Petersen, S.O., Ott, S., Peñaloza, D., Pittau, F., Sathre, R., Spitzbart, C., Takano, A., Toratti, T., Valtonen, T., Vares, S., Winter, S., Zanata, G. (2013). Wood in carbon efficient construction. Tools, methods and applications. Hämeen Kirjapaino Oy.
- Kylili, A., Fokaides, P.A. (2014). Investigation of building integrated photovoltaics potential in achieving the zero-energy building target. *Indoor Built Environment*.
- Lane, T., 2010. Embodied energy: the next big carbon challenge [online Document]. <http://www.building.co.uk/embodied-energy-the-next-big-carbon-challenge/5000487.article> (accessed 9.16.16).
- Lupíšek, A., Vaculíková, M., Mancík, Š., Hodková, J., Ružicka, J. (2015). Design strategies for low embodied carbon and low embodied energy buildings. *Energy Procedia* 83.
- Maturi, L., Lollini, R. (2014). Experimental investigation of a low-cost passive strategy to improve the performance of Building Integrated Photovoltaic systems. *Sol. Energy*.
- reTHINK WOOD, (2015). Evaluating the Carbon Footprint of Wood Buildings. Reducing greenhouse gases with high-performance structures.
- Roberts, S., Guariento (2009). Building Integrated Photovoltaics / A Handbook. Birkhäuser.
- SFOE, 2014. Energy Strategy 2050.
- SUPSI, 2015. Centre Suisse de compétence BIPV [online Document]. [www.bipv.ch](http://www.bipv.ch)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Architecture and Landscape, Frank Lloyd Wright's circular house designs

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**Abstract:** The Jacobs "hemicycle" (1943) is often noted as an early example of the new architectures of the 20<sup>th</sup> century grappling with passive solar design and energy efficiency. It is much more than that. It is a unique moment of creative synthesis wherein the symbolic dimension is brought to the fore as an integral part of unifying perceptions of landscape and architectonics, an example of Wright's concepts of "continuity" and "reintegration." His use of circles and arcs in residential design began with the 1938 unbuilt Jester House project. The also unbuilt designs for John Nesbitt (1941) and Lloyd Burlingham (1942) provide insight into the growing complexity of his use of these forms in relation to specific sites. This effort appears then in the design of the Jacobs hemicycle just as the first designs for the Guggenheim Museum in New York were beginning. Wright extended the layered exploration of perception of self and landscape, form and purpose that the Jacobs design offers into many dozens of others, mostly unbuilt, over the remainder of his career. The most spectacular is the house he proposed in Palm Springs (1950) for Lillian and Edgar Kaufman of Fallingwater.

**Keywords:** Wright, Jacobs, hemicycle, continuity, circle

### Introduction

Frank Lloyd Wright's 1943 design of the "solar hemicycle" for Herbert Jacobs and family is commonly thought of as a landmark moment, as a meeting of the conceptual freedom of the 20th century revolution in architectural form and an early interest in energy conservation. It is much more than this. Conceived as Wright's second career was beginning to flourish, and as he was embarking on the design of the Guggenheim Museum, it represents a milestone in the development of a new concept of architecture in relation to environment. This little building is one of a series of designs created in the aftermath of Fallingwater that can be seen as explorations of his concept of an architecture of continuity, an architecture of reintegration of culture and landscape. The dimensions of this exploration involve impressions of motion, multiplicity, architectonics, and symbolism, all woven together into what he once called an "unbroken wave."

The pivotal design in this sequence is the house designed for the owner of the Johnson Wax Company known as "Wingspread," just as the more famous Administration Building was being constructed. Wright's images of this house generalize an implied rotational motion seen in his rendering of Fallingwater, as the body of that building pivots in space above the waterfall. This occurs again in the aerial renderings for Wingspread, placing the implied movement in the context of the Wisconsin prairies and the horizon. Here the contrast of the rectilinear frame of reference used to control so much of Wright's architecture and a developing symbolism of circles is used to evoke both the processes of nature and our motion through them. This emerging dimension is powerfully expressed in the aerial photograph that replaced the Wingspread rendering in the January 1938 edition of the Architectural Forum that Wright designed. It is perhaps the first aerial photograph he published, saying, "This extended wing plan lies, very much at home, integral with the

prairie landscape which is, through it, made more significant and beautiful.”<sup>2</sup>

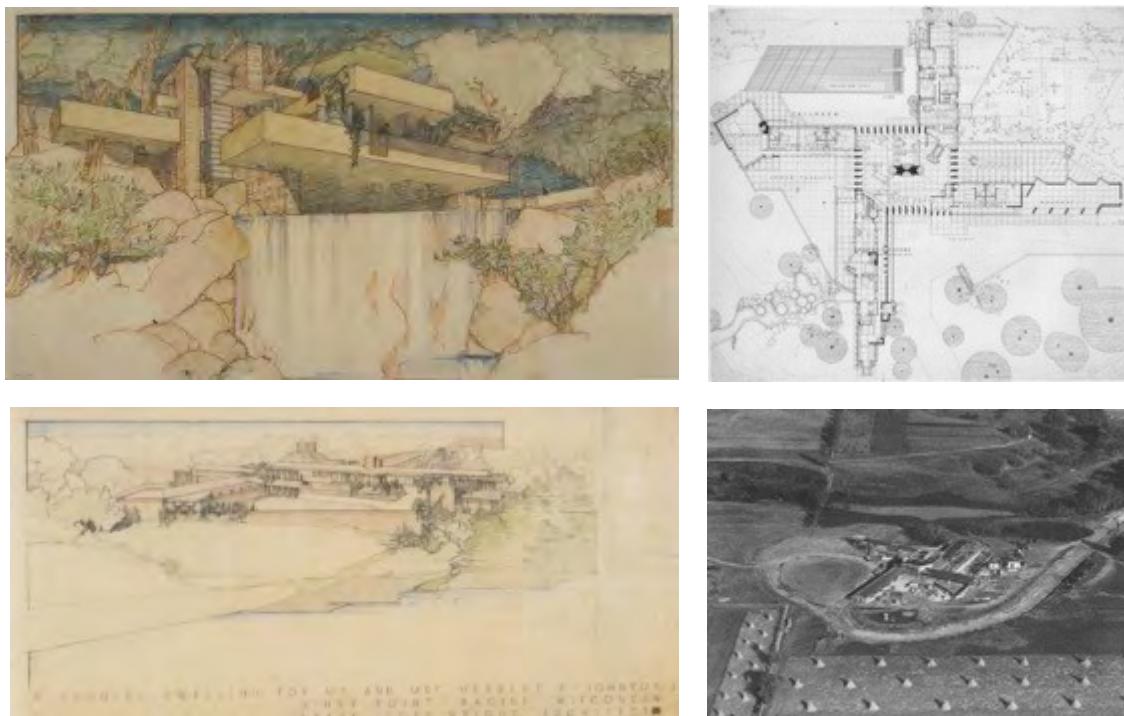


Figure 1. Images of Fallingwater and Wingspread.

#### **Ralph Jester House project, Palos Verdes, CA, 1938**

Wright’s articulation of this dimension began in earnest with the design of a small house on the southern California coast for the Hollywood costume designer Ralph Jester conceived for a site in the Palos Verdes development above Portuguese Bend on the south side of the Greater Los Angeles basin, from 1938 just as Wingspread was being constructed. Especially in the early years before there was much surrounding development, the site provided a unique vantage point that had much to do with the genesis of this groundbreaking design. The location is a small promontory back from the water’s edge, at an elevation of just over 300 feet, repeating the two forms protruding into the bay below. This elevated spot is encircled on the other side by a broad ring of hills rising above 1000 feet that focus the entire valley outward toward the ocean. We can see this in topographical maps just as clearly as the aerial photographs just becoming available in the 1930s.

In the first conceptual elevation of the house a single blue pencil line appears to evoke the ocean horizon so clearly visible from this elevated site. In contrast, the presentation rendering shows the sweeping line of high hills enveloping the other side of the site. A private garden wall to the rear, repeats the arc of these hills, while a pergola on the opposite side reaches toward the sea, projecting outward over the surface of a large pool. One can see this little house engaging perceptions created by the forms of its greater landscape, an abstraction of the structure and qualities defining this place, what one might call its own revealed or governing structure. High to the rear, enclosed and protected by the rounded faces of the encircling hills as the space of the house reaches westward to the setting sun, whose horizontal rays would reach into its center at the end of every day.

The architectonics here can be approached by looking at the graphic vocabulary Wright and the apprentices developed for representing the Usonian house, seen nowhere as elegantly perhaps as in this plan for the first Herbert Jacobs House in Madison. Here, as in

the Wingspread drawings, there is a clear juxtaposition of orthogonal forms used to define and regulate the building, while circular ones portray forms and processes in the landscape. In the Jester design this fundamental distinction is sharpened. Then, in the presentation plan we also begin to see for the first time a careful suppression of the abstract grid that provides measure to the landscape in the way in which it peeks up through the almost random patterning of the stone flooring. The orthogonal becoming a kind of framing device only, receding as our attention is given to forms that interact with and interpret the land.

Wright's renderings and model show the large pool slipping forward through a kind of cleft or ravine also seen in the drawings of Wingspread, although neither of these sites had such a pronounced feature. In the underudies for a Jester aerial drawing the many curving elements of the house and various reflections on the surface of the pool, are transformed as cascading rings of water sliding down this ravine to the sea. The pool, its surface just below the stone floor of the house, would have been seen above the plane of the ocean in the near distance, calling it right up to the lip of the floor. It is a form known today as an "infinity" pool of course – but the point being not only that its surface appears to be continuous with that of the sea below, but more potently the water slipping over its edge hides that boundary as does that of the ocean itself at the horizon – bringing the sky into the heart of the house.



Figure 2. Images of Jester House project and site, with first Jacobs House plan graphics.

#### **Nesbitt House, project 1940-41**

Soon after the Jester project Wright designed a large house for John Nesbitt, intended for a spectacular small cove in Carmel, California, overlooking the majesty of the Pacific Ocean. "*The site is almost solemnly beautiful*" the client wrote, "*a gentle, mildly irregular slope of land that drops down to a . . . rugged, private shore.*" And, "*The cypress and pine much battered by the wind in place, . . . other sections sheltered and tranquil . . . A big surf smashing against granite rocks on the ocean exposure, flamboyant and rich as a Wagnerian last act.*"

The edges of the cove are rocky, ranging from an abrupt cliff at the house site to large patterns of broken rock extending hundreds of feet into the waves. While the site itself was filled with many ancient cypress trees battered by the wind, there was a relatively open and level area on the right side as you entered from the street characterized by a steady slope

dropping along a prominent knoll on the left side. Wright brought the drive into the site there, surrounding almost the entire upper area with an unusual covered walkway to create an enlarged loosely treed forecourt that included the gravel drive area. The body of the house was located directly on the knoll, fitting closely into existing features - identifying a dramatic vantage point, perched above the ocean, standing between the sea and the entry court.

Wright placed a small round pool at the heart of this court to mark the beginning of a ritualized path to the sea. From there a monumental set of piers leads to three sets of double glass doors in a curving wall giving into a multi-story skylit and glass enclosed Interior Garden. Once within this cacophonous space one would have seen the ocean in the distance through the open structure of a steel stair rising diagonally against your motion. The curving line of the enclosing glass wall continues to define an exterior terrace beyond which, cascading down the slope toward the sea, is a further progression of pools fed from the water encountered at the entry, falling from one into the next before being discharged to run over the cliff, back into the sea.

The controlling grid of squares used to organize the house is brought to a pivot where the cascade of pools gives way to views of this cliff, with rocks and ocean beyond. The primary orientation of the house appears to be coordinated with the location of a cluster of exposed rocks out in the cove, visible in the distance, pulling the eye to an intermediate point leading to the horizon. The 30 degree angle of the stair marking the shift of the outer edge of the house is barely noticed on the entry level. The effect of this pivot becomes clear as one moves upstairs to a colonnaded Great Hall and a Sea Lounge that swings out to frame the cove and a broader ocean view. This also frames the dissolving cliff line leading out from the house that defines the cove, bordered on this side by an extensive sequence of broken rock and disintegrating cliff edge, pounded by waves. One would see from here the action of the waves above and beyond the layers of the pools, breaking on the rocks below, dissolving the edge of the continent in full view as a kind of, "... Wagnerian last act."

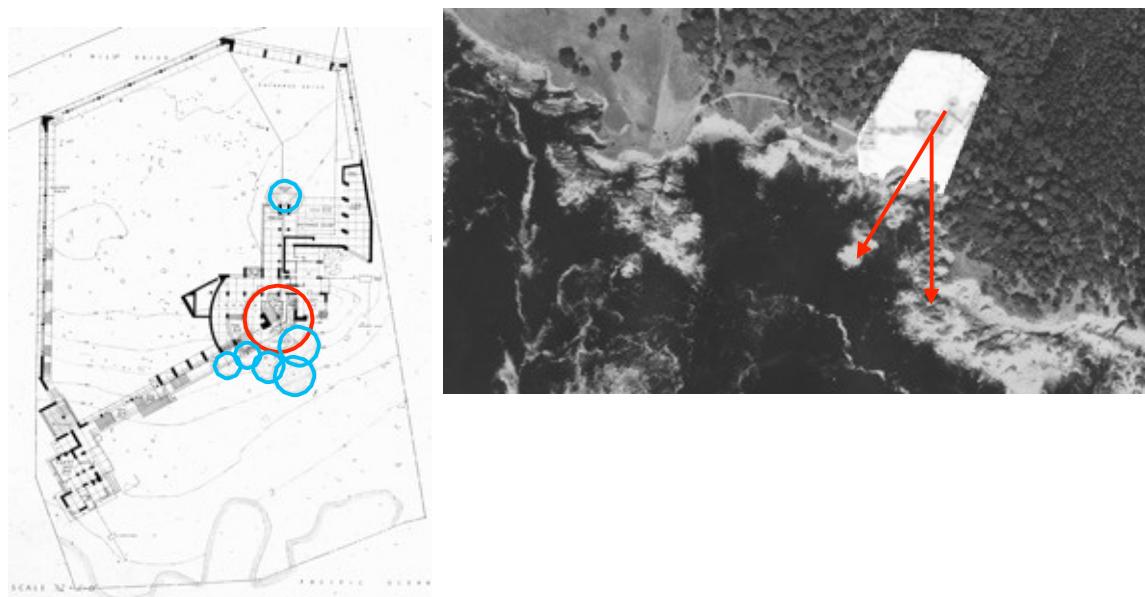


Figure 3. Images of Nesbitt House project plan and site logic.

Engagement with the forces of nature is foregrounded here. As Wright moved from using traditional, hierarchically structured, orthogonal frames of reference as a compositional datum, this design shows him extending the example of Fallingwater, responding to and shaping perceptions of the surrounding environment as a vehicle to order

and conception. This particular project introduces a narrative dimension to the process, using both symbolic readings and motion to ritualize the transition from one state to the next, from the calm of the court and its ancient cypress to the dynamism of the coast. Nesbitt wanted to call it “SeaGarden House,” in recognition of the dualistic nature of his reading of the site. Following the attack on Pearl Harbor and the declaration of war the project did not go ahead.

#### ***Lloyd Burlingham House project, El Paso TX, 1942***

In the next year Wright designed a “ranch cottage” for Lloyd Burlingham overlooking the Rio Grande valley outside of El Paso. This unbuilt project extends the accomplishments of the Nesbitt design by bringing two perceptual events into the formal concept itself rather than lining them up sequentially, a single form that never-the-less is integrally responsive as it engages the surrounding landscape. We see this beautifully here as an arm reaches forward to gather an automobile forecourt close to a small protected yard before leading the eye outward to the sinuous, curving lines of the Rio Grande and trails of smoke floating off into the distance down the valley on the left. In the rendered Jester plan we just saw the underlying control grid was only detected in the nearly random patterns of the stone flooring, clearly present in some areas and wavering in others as the rooms, columns, and furnishings float about with a disengaged unity. In the Nesbit design the grid was interrupted, shifted, washed away by its proximity to the sea. In this Burlingham project Wright utilized the surveyor’s grid in a different way as it anchors the conception of the design to the topography before disappearing entirely. This house was to be composed of arcing lines of enclosure, containment, and circulation organized with respect to two centers selected from grid survey points. One of these, nestled against a rocky outcropping on the high side of the site defines a series of concentric arcs that form the driveway, the enclosed private garden, and the living / bedroom wing of the house. The other located outward toward the vista by means of the 30/60 degree draftsman’s triangle on his drawing board establishes a complementary series of arcs that define the kitchen and service wing about a luna shaped court and pool. Finally a projecting Terrace repeats the figure of the service yard in a kind of moving yin-yang symmetry. The push-pull of the two centers establishes an operational drama for the design which seems suspended between the protective rocky mountainside and the distant river valley, enlivening the prospect and refuge dynamic often referred to in Wright’s domestic designs, allowing the two perceptions to interpenetrate each other.



Figure 4. Images of Burlingham House project and plan.

### ***Herbert Jacobs "hemicycle House, Madison, WS 1943***

The relation of form, symbol, and perception used in that El Paso project appears again in the second home Wright designed for Herbert Jacobs and family in the next year, just as his work on the Guggenheim Museum was beginning. The curving shape of this Jacobs design is governed by a single center divided into two halves. The house's interior and exterior spaces are gathered by the sweeping continuous arc of a single enclosing wall. The obvious redundancy of the circle is reserved for the hearth, a bathroom and utility core, and an inside-outside pool that repeats the dualism of the whole. This pool was initially placed on the central axis of the scheme as seen in this early study before being shifted off center— to create again a kind of disengaged or understated unity. The carefully lowered body of the house looks southward through a sunken garden with a bank of low planting completing the form as it evokes the prairie horizon fully apparent when the house was originally built, capturing the daily path of the sun.

The use of the circle in this design presents a merging of symbolic reference, cognitive process, and cumulative experience as the two sided, narrative dimension of the Burlingham design is folded into a unity, a duality of one where reading the symbol is inextricably woven into the architectonics, it's a stunning accomplishment. Every detail in this apparently simple design serves this purpose. Note especially the horizontal line of the suspended bedroom loft moving continuously just inside the steadily curving wall of the glass French doors, itself comprised only of tall vertical frames uniting the inside and outside with the sky. The intermediate horizontal seen in photos was added by Jacobs during construction and was not part of Wright's original design.



Figure 5. Images of Jacobs "hemicycle" House and plan.

### ***Kenneth Hargrove House project, Orinda CA 1950 / J. J. Vallarino House project, Panama City, Panama, 1953-7***

The tightness of unity in this hemicycle strategy was loosened as Wright encountered various landscapes over the coming years. Designs such as the several each for Kenneth Hargrove and J. J. Vallarino utilized multiple centers for sites in Orinda, CA and Panama. They share with the Jester and Burlingham plans a relationship to sites with distant views backed by rising ground utilized to create a sense of sanctuary. In these designs the steady datum of a constantly curving rear wall is countered by a polyphony of arcs about many centers describing activities of all kinds including living rooms, dining areas, terraces, playrooms, and finally pools held out toward the vista. Moreover, this occurs at different levels as the living rooms rise toward the view, the dining areas slide off toward the kitchen and playrooms, while an upper bedroom wing hovers privately in the middle of it all. Shifting, sliding, moving definitions of enclosure gathered together into one continuous reach outward toward the natural world. In these, and many other unbuilt circular themed designs, Wright

expanded the Usonian geometric framework with the perception of enclosure projected outward to engage features of the landscape as a new architectonic of “continuity”.

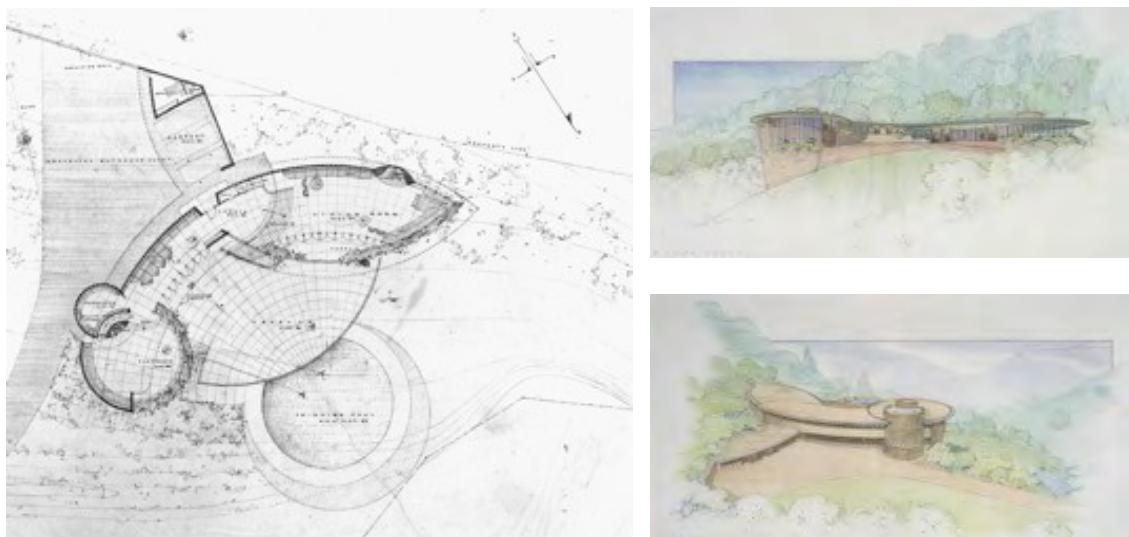


Figure 6. Images of Hargrove House project and plan.

### **Lillian Kaufman "Boulder House" project, Palm Springs, CA, 1950**

In 1950 Wright offered Lillian Kaufman one of the most remarkable designs of his career, as a complement perhaps to Fallingwater, built for her husband almost two decades earlier. This house, meant for a desert site in Palm Springs an hour and a half from Los Angeles, was to be composed of a central element surrounded by a pool and entered by bridges, flanked by outstretched dining and guest pavilions. The simple organizing idea of this "Boulder House" seems almost obvious at first glance, given in the contrast between the three parts making up the body of the house and the expanding circles of court, yard, and boulder strewn landscape. The one seeming contingent, the other totalizing. But the interaction of forms seen in the drawings is of course only part of the story as these are animated by intended relationships to the surrounding landscape. We can see an indication of this in the grouping of trees shown in renderings and plan rising toward the nearest of several ridges that extend into the canyon along its western edge, establishing an affinity with these as they march off into the deep perspective of Palm Canyon and the Santa Rosa Mountains.

One's experience here would have begun with a central forecourt for the automobile, abruptly half lawn and half gravel, framed by the carport wing that encircles the rising stone mass of the hearth which anchors the composition. The entryway pulls toward that distance along the curving side of the dining pavilion, up across a bridge over the pool before being swept into the living room which itself follows a counter motion defining the central luna of the house. It is a process made of fluid changes of direction and orientation, through compressive spaces then expansive vistas as the house curves around you, constantly changing the frame of reference to it and to the ever present visible world outside.

The aerial perspective shows the house's luna shaped masses strewn across the desert floor in dialogue with the mountainous forms pulling one's eye to the distance. The design resembles an orrery, a dynamic moving model of a solar system showing the orbits of planets and other bodies around a central point, yet without ever stating a totalizing order clearly. If you follow your eye as it scans the rendering in a constantly moving dialogue between the lines of the building and the lines of the earth, everything is akilter, off axis, slightly dislocated, creating a spatial experience more like those we find in

the natural world where we establish frames of reference with our own perceptions constantly as we go along. It is a new architecture, the epitome of the dozens of such designs Wright proffered over the last decades of his life, few of which he was able to build, and none at this scale of richness.

In each of these cases Wright identified an experiential aspect of the natural environment as the basis for the placement and orientation of the design, and as the genesis of its formal language, its specific architectonics, and indeed its aesthetics. Each emerges out of something he found in each place, leading our perceptions to a sense of continuity with the natural landscape. He spoke about this in his London lectures, "We are talking about the countryside itself developing into a type of building in which will lie naturally building becoming part of the countryside, building belonging there naturally with grace. . . . The more of such buildings we have in the country the more beautiful community life will become and the less you will be aware of the fact that buildings are there at all as an intrusion."<sup>3</sup>



Figure 7. Images Kaufman "Boulder House" project and plan.

## References

See correspondence N030C05: Alofsin, *Frank Lloyd Wright: An Index to Taliesin Correspondence*, NY. 1988.

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<sup>2</sup> See *Architectural Forum*, January 1938. Page 56.

<sup>3</sup> Wright - *An Organic Architecture, The Architecture of Democracy*. Lund Humphries & Co. LTD, London. 1939.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## An Evolution of Sustainable Aesthetics

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**Abstract:** This paper will reflect on an exploration of the aesthetical influence of the sustainable architecture discourse from a historical and contemporary perspective. It aims to understand the link between different sustainable architecture movements, their labels, implications and subsequent aesthetics. This paper is framed within the understanding that while sustainable architecture has showcased ethical technology, it lacks the holistic aesthetic language needed for the discipline to progress. A discussion of literature concerning sustainability, architecture, and aesthetics, articulating the particularly overlapping relationships between these three discourses initiates this paper. This analysis is then compared with a study of the sustainable architecture discourse after the 1960s. This analysis is conducted to outline the progression of not only theoretical advances and philosophical grounding but also their aesthetical influence both on alternative architecture and the everyday. In continuation, a visual analysis of selected case studies, both historical and contemporary analyses visually what different theoretical concepts are implemented into different design aesthetics. Initial findings emphasise the importance of understanding the origins and implications of sustainable design choices. By understanding sustainable theoretical groundings and their associated aesthetics, there is an opportunity for a new ethical and aesthetical dimension to emerge.

**Keywords:** Sustainable architecture, aesthetics, history, eco, green

### Introduction

“The ugly truth about sustainable design is that much of it is ugly” wrote Lance Hosey (2012) in the opening pages of his book ‘The Shape of Green: aesthetics, ecology and design.’ Hosey (2012) continues with this quote from the 2009 American Prospect “Is ‘well-designed green architecture’ an oxymoron?” Sustainable architecture has the stigma of being all ethics and no aesthetics, but what does this mean for the progression of the field? Contemporary architecture has been overwhelmed with the effects of ‘greenwashing’ and this has resulted in a built environment flooded with conventional buildings smothered in green-technology add-ons. This not only influences the public’s perceptions of what is considered sustainable but creates a sustainable aesthetic which does not represent a truly sustainable approach to design.

Understanding how sustainable architecture has evolved from eco and green architecture helps to illustrate how the current lack of a sustainable aesthetic language has emerged. With growing environmental, climate and global concerns it is even more pressing that our built environment does its part in lessening its negative effects on these issues, however, sustainable architecture will remain fragmented from mainstream architecture if the connection between ethics and aesthetics are not reflected within each other. To elaborate on this, different literature is explored concerning sustainability, architecture and aesthetics, articulating the current discontent with the field, followed by a historical overview

from the 1960s outlining the progressions of the terms eco, green and sustainable. This highlights the societal groundings, technological and aesthetic advances which influence both alternative architecture and the everyday. These periods are then explored through a content analysis of the sustainable visual features of five different architectural examples to understand how and when different theoretical concepts and strategies are implemented into different design aesthetics and what are the resulting visual implications. The historical background is considered as the context in which the buildings developed. Each of the examples are analysed by highlighting, coding and cataloguing distinguishing manifest and latent sustainable visual features. Comparisons and correlations between their historical context and resulting aesthetics are illustrated to understand their development. All of the examples are compared to understand the visual genealogy of contemporary sustainable architecture. Expected results are a description of the visual language of the contemporary history of sustainable architecture and will showcase the plurality of sustainable architecture and indicate the origins of the technological ornamentation which is prevalent today.

### **Discussions of a sustainable aesthetics**

Aesthetics is a complex notion which has been the topic of many debates, it is often considered subjective and a matter of opinion, as is the subject of sustainable aesthetics. Discourse on the topic of sustainable aesthetics appears in few books but is frequently the discussion of magazine articles and opinion pieces from online blogs. The following discussion is outlined not as hard fact, but rather to explore the different concerns which are currently under discussion within the field of architecture. Lloyd Alter (2009) in his article “Why is so much green architecture so ugly?” for the online blog TreeHugger suggests that the field of architecture is experiencing a design crisis and many developments look as though the design was simply forgotten.

Unlike previous architecture movements such as Modernism, sustainable architecture does not have a rigid stylistic dogma or design rules. This means that each sustainable designer is at the mercy of a cumbersome and often contradictory approach to designing. While ethical intentions are often easier to grasp the aesthetical language is somewhat more elusive. Di Carlo (2000) supports and elaborates that existing sustainable architecture only contains ethical action but has no innovative aesthetic language. Hosey (2012) postulates that “technology has hijacked sustainability” and that the art of architecture has been neglected in favour of focusing on the science of building (Hosey, 2007). The focus on technology within sustainable architecture has developed from the need to solve external problems such as the oil crisis in the 1970s, however, the good intention of solving ethical problems has recently resulted in a shallow and fragmented aesthetic approach which often does not communicate the essence of the fundamental sustainable concepts. Geoff Manaugh (2007) in his blog post “Architectural Sustainability” argues that contemporary architects have become masters at the “art of ornamentalizing sustainability” and Mehaffy and Salingaros (2013) also support this notion that sustainable architecture is being adorned with shallow-technical-add-ons and they elaborate that these components are often ‘bolted-on’ without any consideration for their long-term contributions to the ongoing sustainability of the building. All of this is exacerbated by ‘greenwashing’ within the field and often what is discussed as sustainable architecture is merely a shallow attempt at gaining certifications or marketing endeavours rather than a design which at its core is sustainable, eco or green.

## **Historic overview from the 1960s**

The definition of words like sustainable, eco or green are often overlapping and ambiguous, especially with the field of architecture. These architectural approaches have however developed very differently, responding to different societal contexts to produce different forms and aesthetics to represent their underlying environmental fundaments. Before the 20<sup>th</sup> century, buildings were not significant energy users, with electric lighting, heating and elevators relatively new endeavours. Without these technologies, buildings were at the mercy of nature and were consequently designed to defend against the outside elements. At the beginning of the 20th century the technological innovation of using mechanical cooling within buildings had a considerable influence on the form and subsequent aesthetics of the architecture that was to follow. With the introduction of mechanical cooling, buildings now had easy control of their comfort. Raman (2007), explains that it was thought that technology could solve all problem and take care of the consequences of designs which no longer needed to consider environmental issues as energy was considered plentiful. One of the first examples of this technology transitioning into buildings was the New York Stock Exchange building, built in 1903. Following this in the 1930s, the Empire State and Chrysler buildings in New York City were designed with mechanical cooling but still maintained the traditional defensive attitude towards nature and the subsequent art deco forms entailed protective facades with punched openings. The dramatic shift in aesthetics, which was made possible by mechanical cooling is best illustrated by the United Nations Secretariat Building constructed in New York in the early 1950s. There was no concern for the environment or the buildings impact, with the 39 storey single-glazed facades facing east and west, encouraging overheating. In addition, the pitted-stone material chosen for the north-south walls were at risk of freeze-thaw-action and rather than changing material, 39 floors of steam coils were implemented to react to the outside temperature to prevent this (Ramen, 2007). The link between the architect's relationship with nature, technology and energy prices has had a significant effect on the approach and aesthetics of architecture and this can also be traced through modern sustainable movements.

The birth of the modern environmental movement began in the 1960s with the influential writings of E.F. Schumacher, Howard T. Odum and particularly Rachel Carson and her book 'Silent Spring.' For the first time, it was evident that humans had an impact on the environment. During this time grassroots and counterculture movements formed. Homes had become more than simple shelters, accommodating new technologies and equipment (Tabb, 2014). This period developed two different forms of eco-architecture. One being the radical, experimental and socially sustainable architecture formed with the counterculture movement and influenced greatly by Buckminster Fuller and a 'do-it-yourself' attitude. Within the USA this included Drop City an off-grid, bricolage-geodesic-dome artist commune in Colorado built in 1965 and at a similar time Prickly Mountain an array of anti-establishment architecture inventions. Gordon (2008) mentions young architects were in search of new inspirations for aesthetics and form and looked to cocoons, honeycomb, seashell, space ships and seedpods. Buildings were constructed out of earth, recycled or scavenged and off-the-shelf materials. These ventures did not succeed in the long term, Michael Sorkin (1972) in the Architectural Review stated "totem happy dome dwellers, staked out under their geodesic icons in backwoods utopias" were not going to solve the social problem of this period. More conventionally, the other forms of eco-architecture responded to the climate and environment. Three key figures were, Victor Olgyay who wrote 'Design with Climate' in 1963, Ian McHarg who followed with 'Design with Nature' in 1969 and Paolo Soleri who created the

term ‘arcology’ (architecture + ecology) and designed Arcosanti, Arizona in 1970 (Sadler, 2010). Key design concerns and subsequent form for these three approaches included; building siting, orientation, natural ventilation, plan aspect ratios, on-site resources, reduced waste, access to nature, density and typological layering systems. These significant projects, both radical utopias and bio-climatic, may not measure by current sustainable standard. However, responded to the social and political context of their time before energy usage became a pressing concern.

The 1970s brought with it the oil crisis and with it two drastic spikes in oil prices in the early and late 70s. Previous to this energy and emission in general or specifically from the built environment were not a common concern. After the price of oil dropped back to within the pre-crisis range, so did the publics concern. However, building policy, codes and requirements set during the oil crisis remained, which fostered green technology and architecture (Raman, 2007). The romantic intentions of the previous decades started to be shadowed by more measureable approaches to reducing energy. Green architecture emerged in response to this in three main forms; passive solar, off-grid or autonomous and regional design. Passive solar design aimed to use technological advances to create buildings with reduced energy consumption. David Wright, Phillip Tabb and William Lumpkins were three key architects in the ‘70s which used orientation, passive solar systems, thermal mass (often adobe) walls, clerestories, solar shading devices and hot water collectors to generate their form. Off-grid or autonomous architecture developed from the previous experiment buildings of the 1960s. Michael Reynolds’ Earthships’ followed Drop City’s recycled aesthetic with tyres, cans and glass bottles all built within rammed-earth U-shaped structures. Alternatively, Steve Baer tried to integrate these more radical ideas into conventional buildings, utilising polyhedral structures with passive and active solar energy techniques to create what he coined ‘Zomes.’ After the 1970s there was a reduced concern for energy use, this coupled with the development of the postmodern movement created a lull in the development of technologies and instead an interest in comprehensive design (Tabb, 2014). From this, a curiosity towards culture, vernacular and regionalism emerged. Key theorist and architect, Kenneth Frampton and Glenn Murcutt developed parallel concepts; Critical Regionalism and the contemporary vernacular. These concepts considered topography, orientation, light, passive and natural heating and cooling systems when designing for the geographical and climatic context of their site. During this period the price of oil impacted greatly on the architectural typologies. Creating a mixture of environmental technology development, low-tech experimental and hybrid nostalgic regional buildings.

After the UN report, Our Common Futures published the key definition of sustainable development in 1987, the term sustainable architecture grew in popularity. Parallel to this, new and improved environmental technologies emerged along with the insertion of CAD programmes which aided in the creation of new complex and unprecedented structures. Sustainable architecture had moved from the eco and green isolated buildings on the peripheries to monumental, lightweight, highly glazed, high tech buildings in an urban setting. Philip Tabb (2014) explains unlike the previous styles, sustainable architecture “did not look back to the future, but rather projected the future.” Two scales of building emerged; ‘low-tech’ residential models such as Passive and NetZero houses and complex, large-scale buildings, such as the work of the prevalent architects of this period Calatrava, Foster, Grimshaw, Herzog and De Mauron, Piano and Rogers who integrated environmental systems into their building designs. However, this architecture of ‘good intentions’ as Inaki Abalo (2007) words it became an image of sustainability which concentrates on the development of

technical solutions applied to badly conceived buildings (Abalo, 2007). The introduction of accreditations such as LEED and BREEAM did not help this, with a focus on energy savings and the measurable growing exponentially on what were already high-tech buildings designed in isolation to their wider context. Pohl (2011) sees these as a subcategory of green high-performance buildings which are goal-based with measurable parameters for resources and energy conservation. Dean (2009) discusses this as a devolution of architecture due to the implications of applied technology from the 1980s which had led to a techno-science of building. Abalo (2007) during his presentation went on to say "Through the eyes of professional and especially students, this parade of high-tech-drag-queens hardly stimulates creativity." With the turn of the millennium, approaches to sustainable architecture changed slightly. Buildings were no longer considered in isolated and there was a growing interesting in understanding a building in relation to the wider ecological and urban context. A growing interest in biometrics also emerged and with the help of 3D modelling unique biologically inspired forms generated a new aesthetics. Currently, a pluralism of sustainable architecture is developing. Architecture has responded to a variety of different environmental and societal concerns over the years and this has had an effect on the form and aesthetics in which architects use. Understanding how these have transformed in modern architecture is important to the aesthetics of the field.

### **Examples of an eco, green and sustainable aesthetic**

A visual content analysis of five selected examples to represent a cross-section of the development of sustainable architecture is presented below to explore and compare how theoretical concepts were implemented into different design aesthetics and forms. This is supported by outlining the societal and philosophical context to understand how this impacted the visual design decisions.

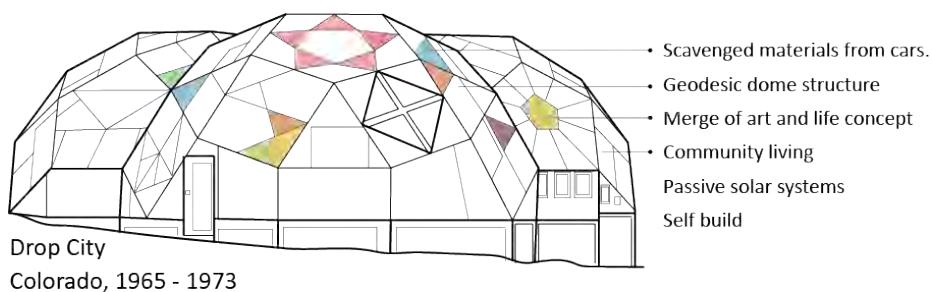


Figure 1. Illustration of one example of an eco architecture aesthetic.

A mentioned earlier, Drop City (figure 1) was an artist commune developed between 1965 and 1973 in Colorado. It emerged as part of the counterculture movements as a form of design activism (Sadler, 2010). Drop City was influenced by Buckminster Fuller's principles and created the first civilian use of the geodesic dome. The societal context of this period greatly informed the utopian ideas which formed this community. The desire to merge art and life and live independently resulted in the use of unconventional shapes, colours and forms. The 'do-it-yourself' mentality which came with this freedom resulted in a somewhat chaotic appearance and use of recycled and scavenged materials, particular metal from cars. The radical aesthetics of these buildings grew out of a social and political sustainability rather than environmental. While this community eventually failed their alternative and radical approach can be seen in later examples.

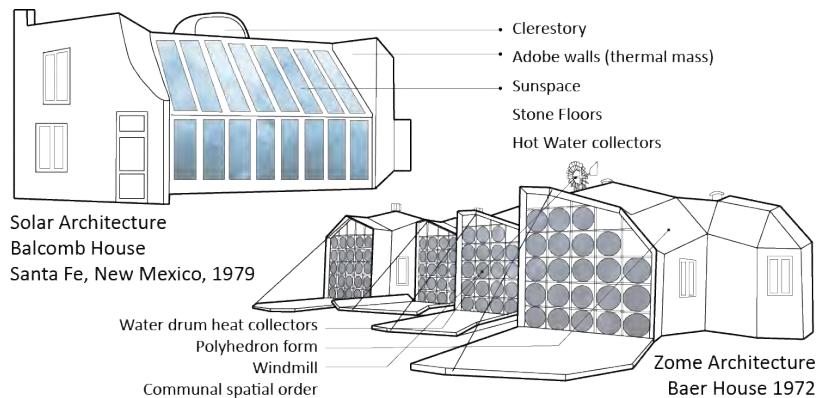


Figure 2. Illustration of two examples of green architecture aesthetic.

The context in which green architecture developed was drastically different to Drop City. Previous insignificant environmental issues were now pressing especially in regards to energy and technology was sought for solutions. The Baer House by Steven Baer illustrated at the bottom of Figure 2, developed from Drop City and Buckminster Fuller's ideas. In addition to the structural efficiency of the polyhedral form, new technology for passive and active energy generation was explored, and this included water drums for thermal mass and windmills. Baer's unconventional typology created communal spatial order and Tabb (2014) described it as "the most recognisable form of rebellion." The Balcomb House by William Lumpkins in 1979 is a well-known example of solar architecture. Solar architecture as mention earlier was designed using passive solar systems to reduce the amount of energy needed. This examples form and aesthetics were designed completely as the subsequent results of the technology needed to achieve the desired energy goals. The material choice of adobe walls was required for thermal mass, the large sunspace which ran along the facade was a necessity for the passive design approach and clerestory delivered the desired natural light and supported hot water collectors. These buildings were designed to explore alternative and unprecedented technology and their aesthetics reflected these unconventional and alternative approaches.

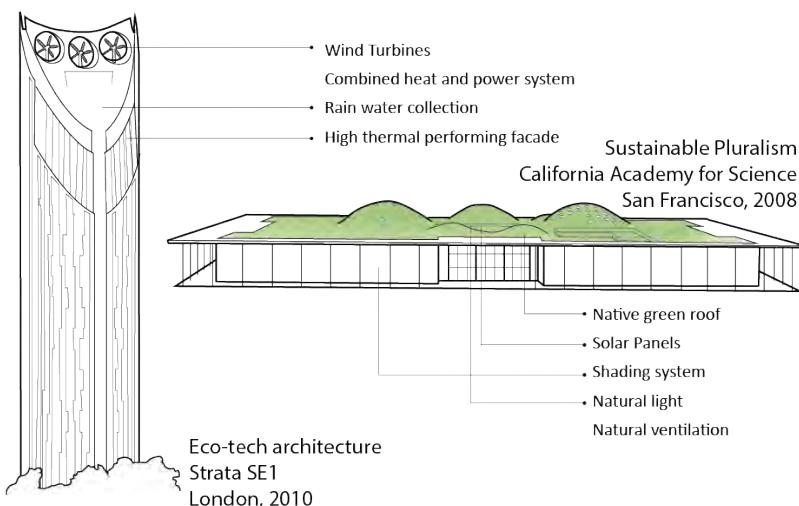


Figure 3. Illustration of two example of a sustainable architecture aesthetic.

These two examples of sustainable architecture in Figure 3 represent two approaches. Firstly, the more integrated approach of the California Academy for Science in San Francisco completed in 2008 by Renzo Piano and secondly, the Strata SE1 building in London from 2010 which highlights an aesthetic of technical-add-ons. Strata SE1 is a 43 storey apartment

building in London which boast three nine-metre wind turbines at the top along with a ‘bespoke’ high thermal performing façade. This building is an example of an afterthought aesthetic which displays sustainable technology with no real consideration of its actual effect as mentioned by Mehaffy and Salingaros (2013) earlier. This building is a prime example of good intentions which failed. To support those three wind turbines, the entire structure needed to be strengthened which required more materials and resources. Unfortunately, while a brave idea, the wind turbines no longer spin which makes the entire building more unsustainable than if they were not there to start with. The lack of holistic thinking with this example led to a shallow, technical aesthetics which unfortunately strengthens the previous discussion that sustainable buildings are ugly and coincidentally this building was voted ‘Britain’s ugliest new building’ by readers of Building Design Magazine (Booth, 2010). The California Academy for Science building is an example of a holistic design which incorporated both natural and environment technical solutions within a cohesive design aesthetic for an incredibly large horizontal building. Solar panels, radiant floors and ventilation systems are incorporated with the large native green roof, natural ventilation and natural light to create both an interesting form and energy efficient structure. This building has a biometric influence in the form of the green roof which is juxtaposed with a relatively convention building below however, this adds to the aesthetic quality. These examples of eco, green and sustainable aesthetics represent only a small section of history but illustrate a narrative of the development of sustainable aesthetics.

## **Discussion**

Current theoretical developments have shifted recently, moving from individual building as experiments to understanding buildings within their wider systems such as in the California Academy for Science (figure 3) which approaches sustainable architecture in a holistic manner resulting in a visually interesting building which merges nature and technology. In contrast, theoretical developments which lean heavily on the notion that technology can solve all, results in building such as Strata SE1 (figure 3) which is a failed attempt of a good intention and without working technology it is actually more resource intensive than is required. The development of each of these example buildings highlights a social constructive perspective in which words, images and artefacts have no inherent meaning and instead meaning can only be understood in relation to the context in which it is ‘consumed’ and analysed. Each building can not be visually understood without understanding the social, cultural and political environment in which it was constructed. These three aspects have had a large influence on the visual latent content of each example and it is obvious that there is direct relationship between the aesthetics and context. A visual transition from the social activism or defiance of the 1960s to a more recent commonplace understanding has occurred in this short history. As the impact buildings have on nature is becoming more evident so is the development of ways in which to solve this. Each decade visually indicates a transition of mans approach to nature, from it being an endless resource to trying to sustain nature for future generations. The form and material use has transitioned from the alternative to more conventional. Domes and polyhedrons transitioned to organic shapes and were then surpassed by more conservative forms adorned with sustainable technology. Some key outcomes of the manifest content were the use of technology, materiality and size development through history. There has been a transition from the reductive perspective of the 1960s, creating efficient forms and reducing waste to the reduction of energy in the 1980s in conjunction with the introduction of technology as a solution which is still prevalent today.

## Conclusion

This paper has outlined how eco, green and sustainable architecture has emerged and evolved since the 1960s, with specific reference to the change in form and aesthetic. After discussing current opinions on the state of the sustainable aesthetic different period were outlined and explore. To understand eco architecture, the social and political context was summarized to situate the experimental and somewhat radical concepts of Drop City and bioclimatic architecture. Green architecture was framed by the oil embargo that influenced the search for alternative energy solutions for architecture. Sustainable architecture was largely influenced by growing technologies and CAD programmes which has allowed for complex and monumental sustainable buildings which are now present in urban environments. With each of these periods of design, new aesthetics emerged and very often were the result of the constraints, reactions and influences of the time. These changes in the aesthetics of the building were visually analysed through five examples in an attempt to form a cross-section of this period of fifty years. This visual analysis clearly shows both the similarities and differences between each approach. It also illustrates how social concerns and technology advancement can radically transform not only how buildings function but also how they are perceived visually. It is clear that with the current plurality of sustainable architecture there is no single sustainable aesthetic language and nor should there be, however, there needs to be a language of integrity that goes beyond the 'greenwashing' examples which currently are flooding our built environments.

## References

- Abalo, I. (2007). Aesthetics and Sustainability. *Sustainable?* Canadian Centre for Architecture.
- Alter, L. (2009). *Why Is So Much Green Architecture So Ugly?*. [online] TreeHugger. Available at: TreeHugger. URL <http://www.treehugger.com/sustainable-product-design/why-is-so-much-green-architecture-so-ugly.html> [Accessed 10 Apr. 2017].
- Booth, R. (2010). *London's Strata tower wins Carbuncle Cup as Britain's ugliest new building*. [online] The Guardian. Available at: <https://www.theguardian.com/artanddesign/2010/aug/12/strata-tower-britains-ugliest-building> [Accessed 16 Apr. 2017].
- Carlo, D. (2014). The aesthetic of sustainability: systemic thinking in the evolution of cities. *The Sustainable City IX*. Presented at the Sustainable City 2017, (pp. 27–38)
- Dean, P. (2009). Never Mind All That Environmental Rubbish, Get On with Your Architecture. *Archit Design*, 79, (pp. 24–29)
- Gordon, A. (2008). True green: lessons from 1960s'-70s' counterculture architecture. *Architectural Record*, 196, (pp. 78)
- Hosey, L. (2012). *The Shape of Green: Aesthetics, Ecology and Design*. Island Press, Washington, DC.
- Hosey, L. (2007). *The Good, The Bad ...* [online]. Architect Magazine. Available at: [http://www.architectmagazine.com/technology/the-good-the-bad\\_o](http://www.architectmagazine.com/technology/the-good-the-bad_o) [accessed 10 Apr. 17].
- Manaugh, A.G. (2007). *Architectural Sustainability* [online]. BLDGBLOG. Available at: <http://www.bldgblog.com/2007/08/architectural-sustainability/> [accessed 4 Apr. 17].
- Mehaffy, M., Salingaros, N. (2013). *Toward Resilient Architectures: Why Green Often Isn't*. Metropolis. Available at: <http://www.metropolismag.com/ideas/sustainability/toward-resilient-architectures-2-why-green-often-isnt/> [accessed 11 Apr. 17]
- Pohl, J. (2011). Sustainable Architecture Concepts and Principles. *Building Science: Concepts and Application* (pp. 225–258)
- Raman, M. (2007). The Good the Bad and the Ugly: A Quarter Century of Environmentally Conscious Design. *Sustainable?* Canadian Centre for Architecture.
- Sadler, S. (2010). Drop City Revisited. *UCDavis Lectures*. UCDavis. California, USA
- Sorkin, M. (1972). A Radical Alternative. *Architectural Record*.
- Tabb, P.J., 2014. *The Greening of Architecture*. Routledge, Burlington, VT.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Architectural design and aesthetics of Zero Emission Buildings: An analysis of perceived architectural qualities in the ZEB Living Lab in Trondheim

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**Abstract:** Technological development of building components for energy efficiency and renewable energy generation has made it possible to conceive buildings able to produce more energy than they actually consume. Zero Emission Buildings – ZEBs - are based on the assumption that the surplus of energy produced by integrated energy systems could compensate their own environmental impact in a life cycle perspective. Beside their simple aesthetics, ZEBs are often the result of complex architectural design processes where morphology and construction are optimized, through the use of advanced simulation tools, towards optimal environmental performance and maximum energy efficiency. Architects assume, in this context, the role of hubs, collecting the complex flow of information provided by the different experts involved throughout the design process, and synthesizing it into a whole. The ZEB Living Lab was designed in order to be representative, for dimension and construction, of a regular Norwegian detached house. Its aesthetic is the result of a complex multidisciplinary design process where students, researchers and industry partners collaborated in the design of an energy positive solar powered house. Its concept was conceived as an internal competition within the MSc program in Sustainable Architecture and later developed at the ZEB research centre at NTNU. The Living Lab has been equipped with a data acquisition system able to monitor environmental performance and energy flow through the building. Today it is used as a laboratory for action research on users' interaction with state of the art technologies for carbon neutrality. In this paper, architectural qualities of the Living Lab, determined on the basis of both numerical analyses and qualitative parameters, will be discussed in relation to both feedbacks provided by different users and collected data.

**Keywords:** Architecture, aesthetics, zero emission, energy efficiency, users.

### Introduction

Nowadays, technological development of building components for energy efficiency and energy harvesting has made it possible to imagine a new generation of buildings able to produce even more energy than they actually consume. According to the Zero Emission Buildings research centre at NTNU, a building can be defined as a ZEB when the energy generated by the integrated renewable energy system is able to compensate emissions: due to the operation of the technical equipment (level 1), due to the operation of technical equipment and appliances (level 2), embodied in building's materials (level 3), released for the construction and demolition of the building (level 4), (Kristjansdottir, T. et al., 2014).

The ZEB Living Lab has been designed in accordance to passive house standards and then optimized in order to reach the ZEB targets (Finocchiaro et al, 2012). Beside their generally simple aesthetics, passive houses represent the result of complex and multidisciplinary design processes. In order to optimize their environmental performance

throughout the year, passive solar heating systems need to be optimized as an integral part of the building's architecture, taking morphology, construction and energy system into account. In this scenario, advanced simulation software assume a fundamental role for optimizing morphology and construction towards optimal environmental performance and maximum energy efficiency. In such a scenario, results provided by simulation tools might determine the building form but also condition the choice of materials, the glass ratio, orientation etc. affecting architecture and housing qualities, such as the relation between indoor and outdoor, or the tight correspondence between form and program.

In such integrated design processes, architects assume the role of hubs collecting a complex workflow of information provided by the different experts involved and translating it into forms based on their experience and visions. In such a process of synthesis, architects should not look for compromises between qualitative and quantitative variables, but rather ensure that those complement each other. Building aesthetics becomes in this context an honest representation of the effort of synthesizing quantitative and qualitative parameters into a whole, reconnecting the way forms look with the way they actually perform.

### **The ZEB LivingLAB.**

The ZEB Living Lab (Figure 1) is a test facility representative of a single-family house, with a gross volume of 500 m<sup>3</sup> circa and a heated surface of approximately 100 m<sup>2</sup>. Its architecture is the result of a complex multidisciplinary design process in which students, researchers and industry partners have collaborated in the architectural design of a solar powered house able to produce more energy than it consumes on a yearly basis (Finocchiaro et al, 2011).



Figure 1. The ZEB Living Lab at the campus.

The Living Lab relies on the integration of three renewable energy systems for covering its annual energy demand: a 12KWp photovoltaic system on the roof, a solar thermal system in the south façade and a geothermal system connected to a heat pump on the north side of the building. Its construction aimed to demonstrate that ZEB targets could be achieved in the climatic context of Trondheim. In addition, the building serve today as a laboratory for investigating users' interaction with state of the art technologies for carbon neutrality. For this reason, it has been equipped with a data acquisition system able to record any kind of information related to environmental performance and energy flow (Goia et al, 2015).

The building concept was chosen as result of a competition run in the first semester of the MSc programme in Sustainable Architecture at NTNU. Throughout the competition students recurred to an extensive use of simulation software of different kind, optimizing the building environmental performance towards indoor comfort while ensuring the production of an amount of energy sufficient to reach the ZEB targets. The winning concept, originally called *FlexBOX*, was based on a versatile construction system making it possible to adjust the building construction in connection with different users and climatic contexts (Haase et al, 2011). This concept was later further developed within the ZEB research centre, resulting in a flexible construction system including three main architectural components: the functional boxes, the transversal partitions and the roof components. The functional boxes were dimensioned in order to contain technical equipment, building skin and furniture in the compact section of 135x420 cm (Figure 2). Transversal partitions, placed in between the boxes, could be adjusted in accordance to different building programs and serve as internal or external partitions. The roof construction, consisting of two large elements disposed between the boxes, integrated photovoltaic system on the outer side and phase changing materials on the inner one.

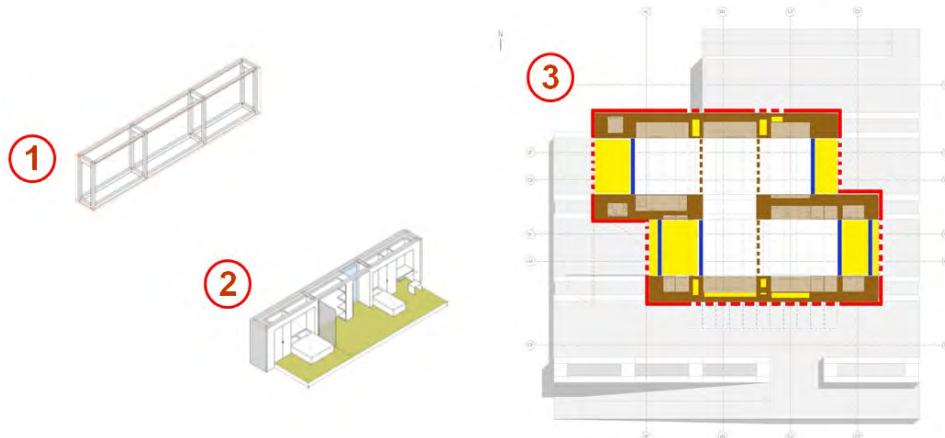


Figure 2. The building concept

The construction of the Living Lab, optimized through different sets of simulations, resulted in a low-transmittance envelope with a glass ratio of 20% circa (Finocchiaro et al, 2012). Walls, floor and roof are all made of a double layer of rock wool insulation with a total thickness of 45 cm. All windows in the house respect the passive house standards with an overall transmittance of  $0,8 \text{ W/m}^2\text{K}$ . The double window towards south, designed as a passive solar heating system, is characterized by a markedly low u-value, varying from 0,65 to 0,69 depending on the ventilation rate within the air cavity (Figure 3). Because of the light construction of the building, solar gains might be responsible, however, for large temperature fluctuations and the risk of overheating in the summer period (Finocchiaro et al, 2016). For this reason, both south and north windows are coupled with an automated control system able to activate, when required, a natural ventilation flow through the building. Skylights towards north can independently be opened to let the exhaust air out through stack ventilation. In the meanwhile, PCM panels integrated in the ceiling construction aim at stabilizing temperature fluctuations within the comfort zone.

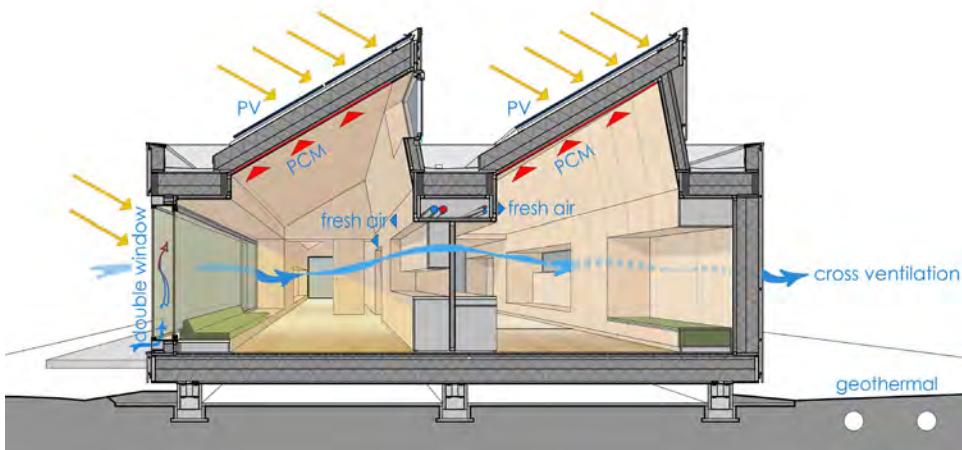


Figure 3. Environmental concept

### **Analysing architectural qualities of ZEB**

Between October 2015 and January 2016, six different groups of users have been living in the Living Lab for three weeks each circa. Users included two young families each with two small children, two senior couples (one of pensioners and one of workers), and two groups of students. Variety among users aimed to unravel if there are any differences in the way users perceive features of zero emission buildings (Korsnes et al, 2016). All of them were invited to take with them any kind of object that could have let them follow their regular living activities and feel home. Users were interviewed before, during and after their stay by an architect and two social scientists from the *Zero Emission Building* research centre (Woods et al, 2016). Questions addressed aimed at understanding how the interaction with integrated technologies could affect their regular living activities. Interviews, transcribed by master students in Interdisciplinary Studies of Culture at NTNU, aimed to give a platform for providing relevant knowledge for future development of green housing.

In this study, we focused on understanding how users experienced those architectural qualities of the Living Lab that were determined by the intention of reducing its environmental impact, and more precisely:

- Space: inner space and floor to ceiling height have been determined optimizing the angle of the integrated solar cells towards maximum energy generation.
- Transparency: was affected by the need of reducing heat losses limiting the glass ratio from 40 to 20% in the latter stage of the design process.
- Materials and components were defined on the basis of simulation results but also with the intention to visually express a prefabricated system based on a clear modularity.

### ***Inner space and functionality***

The disposal of three prefabricated boxes determined the open building plan, organized in two main areas (Figure 4): a living area facing south and a working/sleeping area towards north. Technical room, toilet and kitchen have been aligned along the central axis of the building in order to optimize the distribution of three alternative heating systems, mounted for research purpose (Goia et al, 2015). Supply air terminals have been placed in the living room and in the bedrooms; extract in the bathroom and in the kitchen. The open plan makes

it possible to cross ventilate the building in summer or heat it with only one radiator placed in the middle of the plan; all solutions, those ones, now tested for comfort and efficiency.

The construction of the roof, optimized in order to maximize energy generated by the integrated photovoltaic system, resulted into two slabs tilted of 30 degrees towards south (Finocchiaro, 2012). This represented the opportunity to rise the space between the boxes to an average height of 350 cm circa and catch the daylight coming from north. The high ceilings accommodate a small mezzanine on the top of the bedroom towards west, equipped with a mattress for guests or play area for children.

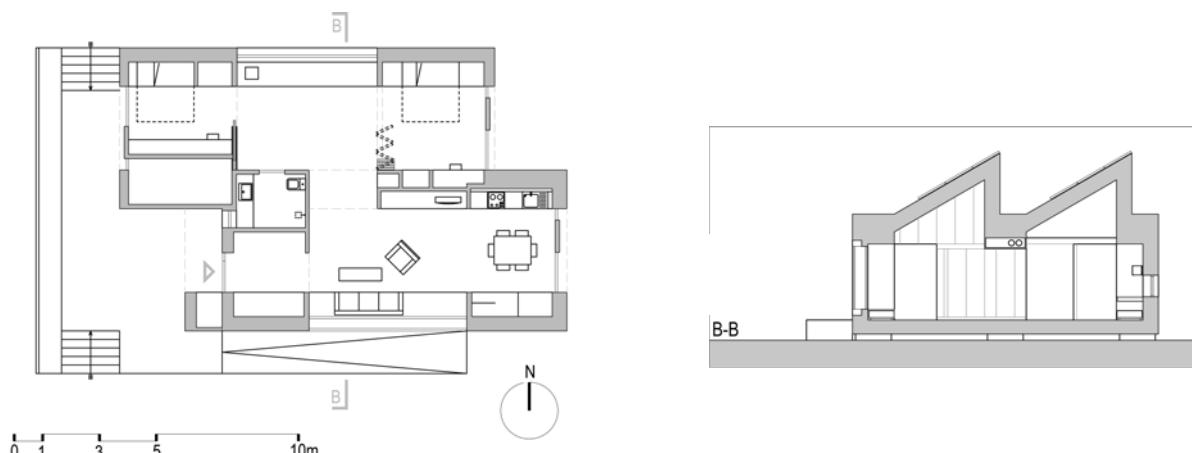


Figure 4. Plan and section of the Living Lab as built.

People living in the Living Lab generally appreciated the spacious interior: "*I think the extra floor to ceiling height provides a nice atmosphere. It makes the room more open and spacious. I want the house to look as nice as possible when I have visitors, so then I use to open all the doors to make the house as open and spacious as possible*" (young family woman). Even more important, users recognized the extra height as a quality given by the necessity of optimizing the position of the solar cells, recognizing the integration of a solar system as the opportunity for giving a different quality to the inner spaces or allocate new functions. "*It is probably like that because it has to but it also provides a lot of space*" (quoting one of the family males).

The open plan was appreciated by some while others felt that the house lacked in privacy and they would have appreciated a more extensive use of flexible partitioning such as the "*magic!*" one between bedroom and studio (young woman with children). The open plan was considered by many "*a bit unusual according to the Norwegian climate and lifestyle*". A door between entrance and living room would have avoided temperature drop due to cold air from the outside whenever the entrance door is open. Moreover, the open plan made it difficult to differentiate temperature between living and sleeping area, something particularly dear to Norwegians for which a temperature of 16 degrees is generally appreciated during night time. Moreover, the sliding door as the only possibility for getting fresh air in the bedrooms affected indoor comfort as this was perceived as a limit to adjust indoor temperature during the night time.

### **Materials and construction**

The construction of the LivingLAB has been optimized through different sets of simulations resulting in a stringent envelope characterized by low transmittance and a glass ratio of 20%

(Finocchiaro et al, 2012). When possible, materials with minimal embodied emissions were identified. Walls, floor and roof are made of a double layer of rock wool insulation - with a total thickness of 45 cm. A light construction system was chosen also because of the intention of prefabricating the building construction. Lightness would have facilitated transportation of components and construction. According to the concept, furniture, made of ephemeral modular elements, could have been moved according to different users' requirements. It was the architects' intention to express building modularity and the use of the light construction in the inner surfaces. For this reason, the surface wrapping the interior is made of birch plywood panels of a constant width of 60 cm (figure 5).

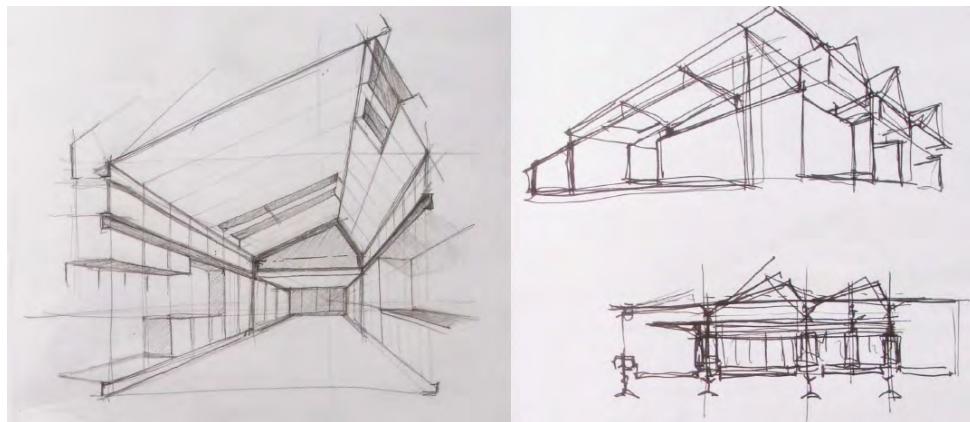


Figure 5. Sketches

Modularity within the LivingLAB was generally perceived as a positive quality, resulting in inner spaces characterized by "*aesthetical calm and comfort*" (*a young female*). Most people felt the wooden surfaces as pleasant, giving "*the feeling of living in the top of a three*"; while others attributed to them the perception of dry air. Inner space geometry, with the two pitched roofs between the boxes, was designed in order to catch daylight from the north, creating variety of colour and changeability throughout the day. However, skylights were reduced to the minimum because of the elevated heat losses due to exposing glass surfaces towards north and the interior turned into a homogeneous surface characterized by a "*white-wooded monotony*". Some interviewees describe the inner spaces as sterile while many expressed the desire to use the high wall-area as the opportunity to make the house more homely with variable surfaces: large paintings, textiles or larger skylights providing an extensive view to the sky.

### **Transparency**

According to the concept, transversal partitions between the boxes should be adjustable in relation to different users and contexts. The construction of external partition in the Living Lab towards east and west was optimized in order to limit heat losses while still let a sufficient amount of daylight indoor (Finocchiaro et al, 2012). Interviewees perceived indoor spaces as with plenty of daylight and with a good visual connection to the outdoor. "*When we come home after being away the whole day, I think it is the flood of daylight that provides the home-feeling. Because we have daylight - lots of daylight from all directions*" (*a female senior*).

The LivingLAB has been placed in the University campus, to ensure visibility and accessibility in connection to public events and research projects. Because of this, openness was soon turned into a privacy issue. Some experienced the connection with the outdoor "*a*

*bit weird*" and uncomfortable, especially in the beginning, when passers were curiously looking into the house. Most people placed the blinders from eye-height and down to be able to have daylight and view to the sky. However, people recognized this as a necessary compromise and simply imagined to live in the same house at their own site "*maybe with a winter garden outside the kitchen, and with the daylight along the floor from floor to ceiling height windows. I think that would be very nice!*" (Male senior).



Figure 6. Interior view

### Summary of main findings

On the basis of the study conducted, interviewees reported the experience of living in the LivingLAB as a positive one. The residents perceived the building as an ordinary house and related their experience to functional or aesthetic qualities more than to the technological content of the building. During their stay, users were occupied with their own well-being and those practical issues that would have let them conduct a regular life and feel home. Throughout the interviews, people referred, more or less critically, to the open plan, inner surfaces, daylight conditions and connection with the exterior. Relatively little attention was devoted to the interaction with integrated technologies, if not few considerations about night temperature and daylight distribution. Variation in the collected feedbacks depended more on individual preferences rather than on the kind of household. People were always referring to their previous house as a term of comparison to the Living Lab experience.

Feedback collected from the different households gave evidence of the importance of balancing quantitative and qualitative parameters in the architectural design of green buildings. "Home cultures and residential practices regarding airing practices and the desire for atmosphere, well-being and sensory experiences" can markedly influence energy use in buildings and "must therefore be taken into account" throughout the whole design process (Wågø and Berker, 2014).

The construction of the Living Lab aimed to demonstrate that Zero Emission Building targets could be achieved in the climatic context of Trondheim. The development of a unique concept, originally based on a prefabricated construction system, also aimed to give evidence that, within the ZEB targets definition, a wide range of architectural solutions can be developed. In this regard, the architectural design and construction of the Living Lab aimed to demonstrate how the effort of minimizing environmental impact of the built environment could become the opportunity to define inedited architectural scenarios.

## Acknowledgments

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## References

- Kristjansdottir, T. et al. (2014). *A Norwegian ZEB-definition embodied emission*. ZEB Project report 17. Oslo: SINTEF Academic Press.
- Finocchiaro L., Dokka T.H., Gustavsen A. (2012). *+hytte. A Versatile Construction System for Zero Emission Buildings*. ZEMCH Conference. Glasgow, 20-22 August 2012.
- Finocchiaro L., Haase M., Wyckmans A. (2011). *+hytte. Sustainable design among didactics, research and social awareness*. SB11 Conference. Helsinki, 18-21 October 2011.
- Goia, F., Finocchiaro L., Gustavsen A. (2015). *The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zero emission house for engineering and social science experiments*. 7. Passivhus Norden conference. Copenhagen, 20-21 August 2015.
- Haase, M., Finocchiaro, L. (2011), *Building form, climate and energy supply system in a passive house building*, 4th Nordic Passive house conference 2011. Helsinki, 18-21 October 2011.
- Finocchiaro, L., Georges, L., Hestnes, A. G. (2016). *Passive solar space heating*. Chapter in *Advances in Solar Heating and Cooling*. Cambridge: Woodhead Publishing, Elsevier.
- Woods, R., Støylen Korsnes, M., Berker, T. (2016). *Making a home in Living Lab: the limitations and potentials associated with living in a research laboratory*. DEMAND: Dynamics of Mobility, Energy and Demand Conference. Lancaster, 13-15 April 2016.
- Støylen Korsnes, M., Berker, T. Woods, R. (2016). *Compliance and Deviation: How occupants interact with a high performance zero emission building*. DEMAND: Dynamics of Mobility, Energy and Demand Conference. Lancaster, 13-15 April 2016.
- Finocchiaro, L. (2011). *+hytte. A Versatile Construction System for Climate Adaptability*. Architecture in the fourth dimension. Open Building conference. Boston, 15-17 November 2011.
- Wågø, S. & Berker, T. (2014). *Architecture as a strategy for reduced energy consumption? An in-depth analysis of residential practices' influence on the energy performance of passive houses*. Smart and Sustainable Built Environment 3, pp. 192-206.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Contributions to Sustainable Construction Socialisation Project and Construction of Secondary School in Mendoza, Argentina**

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**Summary:** The main reasons that increase the interest in environmental matters within the field, are connected to technology and material systems. This paper shows that the material- construction stage in an architectural project is a determining factor in the architecture / sustainability equation. With that purpose, a study case is introduced. It describes in detail the project's first construction stage of a secondary school building in the province of Mendoza, Argentina. There is special emphasis on material system criteria, as well as the chosen applied technology, construction technique and materialisation, specifying their compatibility with environmental purposes. Moreover, it will be described how the programme, urban landscaping, the building position in the plot and the resources' economy, together with the constructive system, determine the building's space construction. From this analysis it is deducted that the proximity between the building's materials used and construction techniques, plus the relevance of its space construction, create certain tension regarding sustainability correction criteria.

**Keywords:** sustainability, rationalisation, materialisation, socialisation.

### **Introduction**

There are various causes for our concern regarding the open possibilities that construction techniques and sustainability problems present to architecture from a material point of view. They are diverse, but converge in one point: technology as a problem for architecture.

From a material point of view, buildings' energy self-sufficiency and sustainable construction imply the application of thermodynamic principles as well as the equation resources / energy cost. Different materials thermo-physical properties are brought into play in order to choose and select the elements that are part of it.

Nevertheless, sustainability entails new ways of material and construction systems organisation as well as new building behaviour in relation to the environment. As Ábalos asserts, it represents a technical change regarding a material culture based on mechanical principles towards thermo-dynamic principles (Ábalos, 2015).

This shifting from the traditional tectonic system towards a thermo-dynamic system based on energy, that Javier García, offers alternatives to propose a model to the emerging ecological conscience (García Germán, 2010).

## Description

Architectural products that have been conceived under some sustainability considerations, hold a series of principles which are based on the reasonable use of resources and environmental economy. Certain criteria is imparted in a normative way -without being a prescriptive list- favouring less energy-requiring construction and contexts integrated within their environment. These principles form part of an architectural culture that has never been appeased in spite of the prosperous crystal boxes world that adapted to any place.

Consequently, the environmental issues that are relevant to the field create an ecological conscience model, producing tension between developed construction tendencies that demand an ever increasing use of material and a progressive deterioration of the biosphere.

By this we mean the indiscriminate use of artefacts installed at any price; with air conditioning becoming too important as a mechanical conditioning and immunological isolation system (Sloterdijk, 2010). They break however, with the authentic technical side of architecture that Banham supported, and turn into mere forms of expression (Banham 1975).

However, good quality and consistent low energy-requiring architecture has its roots deeply inserted into architectural culture.

More than just another optimistic technology approach that results in formalistic practices that are generally unfortunate, this is to us an opportunity to investigate the necessity of incorporating instruments to the project's process. We have the chance to think of material organisation in the terms of a dynamic interchange that is both coherent and in agreement with the building form organisation. All this involves providing methods and object conceptualisation forms without losing architectonic identity.

That gives origin to our interest in the contribution to sustainable building socialisation through materialisation.

Architecture being an activity that influences material culture, its link with construction is a determining factor. Nevertheless, having a historic side and consistency in their form, the products of this activity refer to an open system that adapts to different ways of thinking, feeling and acting choosing the most favourable conditions to each case to adapt it to human lifestyles.

Just as the material system's selection stage in the architectonic process is a determining factor in a product's conception, construction techniques are the means by which matter is organised. Furthermore, according to the tendency shown in the past, the direct link that construction techniques have with their physical environment, social context and culture, is essential.

Currently, a building's project that is constructed in a specific space and time, should contemplate the transformations and consequences that it causes in the local and global physical environment. With this purpose, parameter strategies are included in the project's process, to give energetic dimensions to environmental behaviour. Still, the model reveals a parallel between the construction process rationality and structural performance, which is part of a mutual agreement consisting of an instructive historical horizon. That is, architecture's ability to transform and adapt to the physical, social, and cultural environmental conditions.

Furthermore, the interest in restrictive sustainable strategies, focuses again on conceiving from the material point of view, which was typical of the traditional architectural culture tradition until mid-twentieth century.

There are mainly two factors that aim to a rational type which provides guidelines that connect the different interacting parts in a context of conservation and adaptability (Gelardi, et.al. 2014). These factors are the sustainability criteria concerning energy requirements involved in the construction, materialisation and functioning processes; and the consideration of the chosen energy resources.

However, this combination of physical and functional units, acquires internal coherence according to the connection and balance criteria that belong to a specific way of conceiving. As Piñón said, a way of conceiving capable of combining construction systems logic with matter organisation logic or logic of the form (Piñón, 2009). As it's been said further above, from a sustainability point of view, attention is given not only to construction techniques, but also to a systematic conscience that gives order to the construction of the form. This is the approach in our analysis: In the same way we focus on material systems guided by sustainability criteria, we equally focus on the methods operating in the constitutive aspect that characterises architectural products which are successful thanks to their material quality and formal consistency.

### ***Study Case***

The following is the Project and 1st stage construction of a Secondary School building in Mendoza. The building is located in the City of Mendoza, capital city of the province of Mendoza, in the Centre West of Argentina. Situated in the Andes foothills, on the border with Chile, Mendoza is an arid area, with a high risk of earthquakes. The architectural programme consists of 4.644 m<sup>2</sup> of roofed floor area divided into two main buildings. The central building for classrooms and study rooms is 110 meters long on three different levels. The multi-purpose room has a surface area of 942 m<sup>2</sup>. There is a roofed area to practice sports, changing rooms and a gym. The project has five construction stages.

### ***Urban Landscape Settings***

The property is located in the District of Godoy Cruz, within the metropolitan area of Mendoza City. Situated in a two-road junction in a low density residential area, it's bordered by old railway operators' houses in the West, and by Benegas Recreational Park in the South. (Figure 1)

The plot has a surface area of 1ha 1,395.80 m<sup>2</sup>, with an average slope of 2% towards the North East.

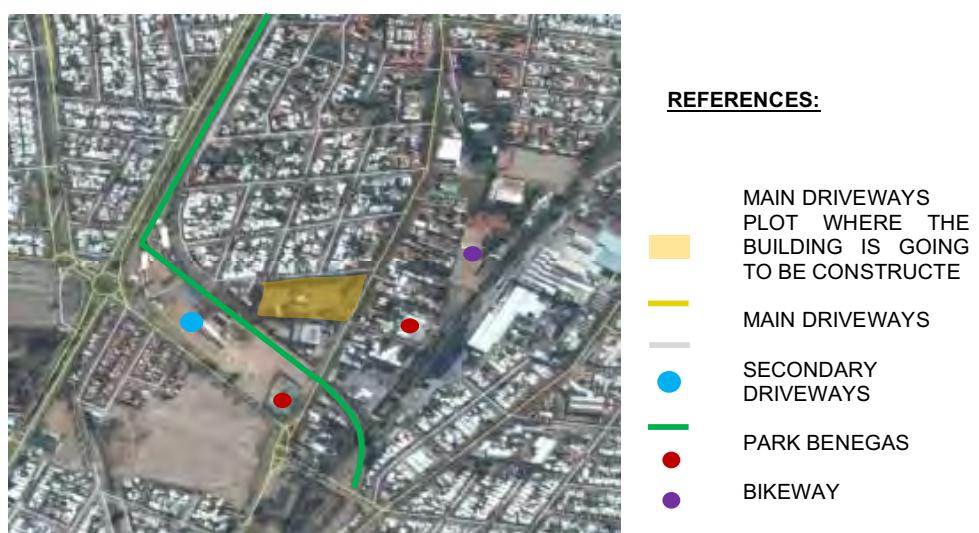


Figure 1. Campus position within the urban local area. Main activities that are not part of the residential area are marked

## Climate

Godoy Cruz is warm or hot in summer and cold in winter. Rain is scarce in winter and common during the summer months. (Figure 2) The wind is relatively calm and it mainly blows from the S-SE-E quadrant in summer (60%) and S in winter (25%). Occasionally, there is risk of Zonda wind, which is a very hot dry strong wind with a considerable amount of dust in suspension. (Figure 3)

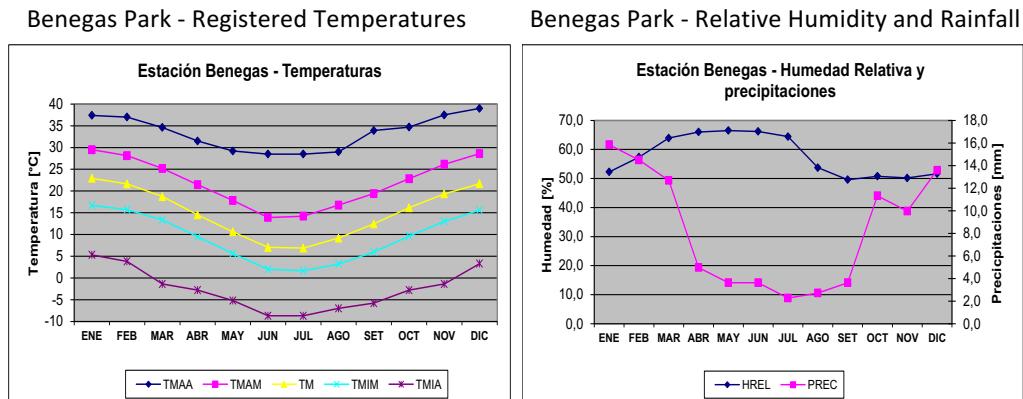


Figure 2: (Left) Absolute Maximum Temperature (TMAA), Maximum Average Temperature (TMAM), Average Temperature (TM), Medium Average Temperature (TMIM). Minimum Absolute Temperature (TMIA)

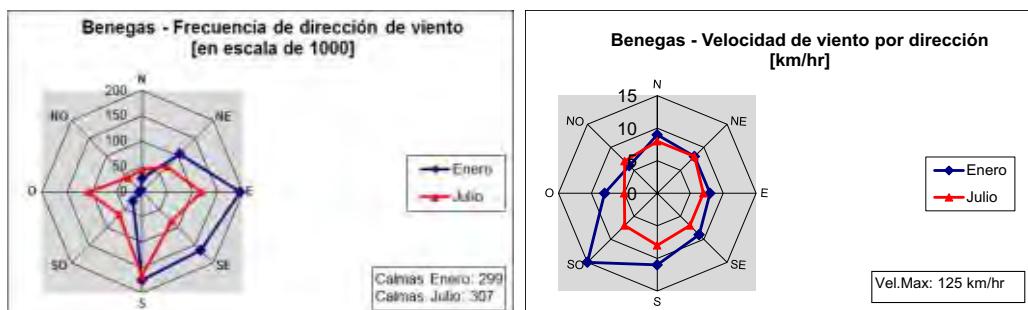


Figure 3. (Left) Wind direction frequency during January (Representative of the summer) and July

## Building's position in the plot

The 110 m long central building, goes from East to West, and the multi-purpose room is in the corner. The campus has a 3000 m<sup>2</sup> garden that integrates the paths and surrounds the space, turning the plot into the area's microclimatic lungs (Figure 4)



Figure 4. Buildings position, Access driveways and paths

### ***Structural System***

The structural system is materialised with precast reinforced concrete panels mounted on site. Transversally, the earthquake resistant structure formed by columns and beams linked by post stressed hybrid joints that support premoulded slabs at different levels. These floors have the sufficient resistance and rigidity to re distribute earthquake actions on their own level (Figure 5).

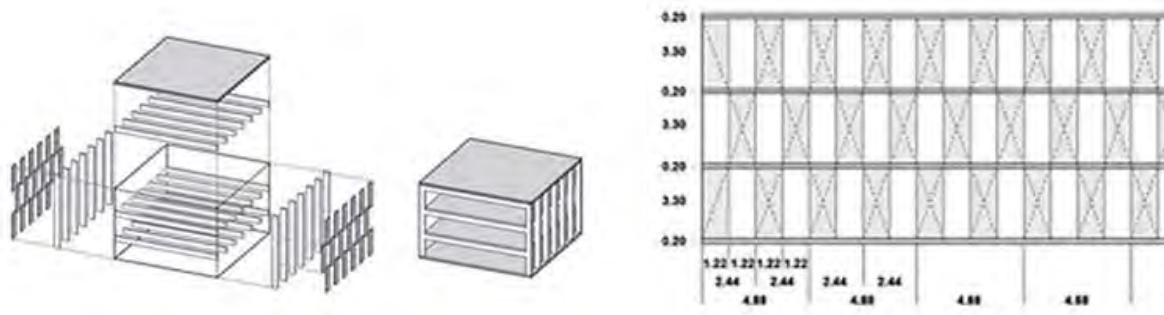


Figure 5. Premoulded and Poststressed Elements Structure System

Longitudinally, the earthquake resistant structure is materialized with crosslinked partition walls, which at the same time, are linked with the second level premoulded partitions. These crosslinked partitions and the resulting windows on the front walls, are necessary to achieve structural rigidity. (Picture 6)



Picture 6. Construction and assembly of the structure and panels

### ***Resources Economy***

The building is strategically sustainable, having been designed using common sense. It faces the North so as to obtain the most solar exposition possible. The screened porch alongside the building, creates a greenhouse effect in winter, conditioning the area. The load bearing structure is at the same time the envelope and enclosure structure, as well as shading for the facade. The materials used for the flooring and envelope structure accumulate energy in their thermal mass. The system is completed with energy conservation depending on the thickness and the concrete's thermal transmittance. In summer, the covered area is opened, allowing the rooms to have shading and generating draughts.

The following figure shows the Ground floor and the two tall plants of the building (Figure 7)

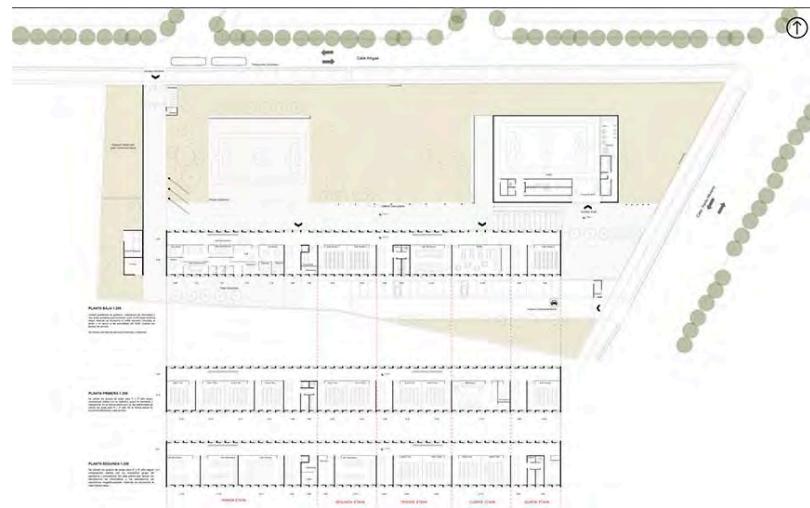


Figure 7. Ground floor, 1st and 2nd floor where screened porches and rooms are shown.

### **Bioclimatic Criteria**

According to the programme's demands and the local climate's characteristics, the proposal has five main sustainability approaches with the purpose of achieving energetic efficiency. They are as listed below.

1. Direct Energy Saving: The North facade and the porch create a greenhouse effect and accumulate energy in the floor's thermal mass. The screened porch's glass panels' surface area is of 43% and allows an energy saving of about 39% compared to the same building conceived without these considerations (Figure 8).

2. Solar Exposure and Natural Ventilation Control: In summer, the facades work as a passive cooler, allowing nocturnal cross-ventilation.

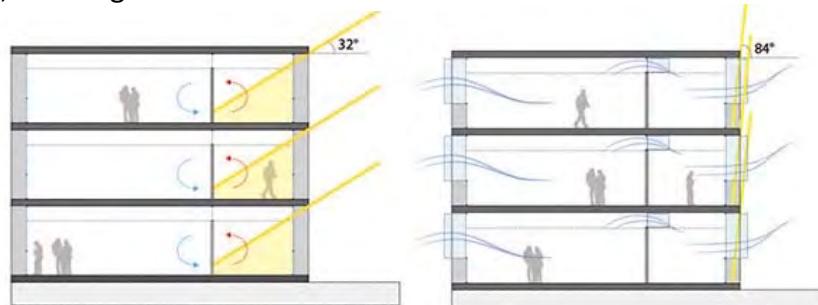


Figure 8. Direct saving system facade – Cross ventilation and facade shading

3. Energy Accumulation: The North facade allows solar exposure, making it possible for heat to accumulate in the materials during autumn and winter. In summer and spring it gets shade during the day allowing nocturnal cross ventilation to cool down the building's thermal mass (Picture 9)



Picture 9. North Facade – Direct saving system. Interior sketch and existing porch photo

4. Energy Keeping: The appropriate thermal insulation is incorporated both in roofs and in aluminum window door frames, using watertight double glazed window panels.

5. The FAEP (Factor Area Surrounding Floor) is the indicator to evaluate the building's exposure to the exterior; it's the ratio of thermal envelope surface area to the floor area (Esteves, et.al.). The lower the HLFF, the lower thermal interchange will be, and also the smaller envelope surface area and floor surface area.

Table 1. Thermal Balance. Bioclimatic Adapted System and compactness of the building's volume

Fracción de Ahorro Solar - Sistemas Pasivos (FAS)		
Sup Exp	FAS	
Ganancia Directa - Galería Invernadero	392 m <sup>2</sup>	42.80%
Solar Saving Fraction – Passive Systems Exposed Surface Area Direct Saving – Screened Porch Greenhouse Effect 392 m <sup>2</sup> 42.80%		
Coeficiente Global de Pérdidas (G)		
	Area (A)	(A). (K)
CNP		7083.195
Vent. norte	391.98	1685.514
Vent. este y oeste	29.64	127.452
CGP		8876.161
Factor "G" - Norma IRAM 11604		0.7

The ground and first floors, have a HLFF of 0.47, while the third floor's HLFF is 1.4. This difference is caused by the roof exposure. Using thermal insulation on the terrace has been considered to reach levels which are even higher than the standards required by the national regulator entity IRAM and with an international point of view (LEED) (Table 1).

6. Energy production by photovoltaic technology: Bearing in mind the actual energetic demand (164Kw), and trying to minimise the network's energy consumption; the plan is to install and distribute photovoltaic panels by polycrystalline or monocrystalline silicon modules, all connected among themselves. The park's rated power will be 50 kW.

There will be 200 polycrystalline solar panels of 250w with 1,65m<sup>2</sup> surface area each. They will cover a surface area of 165m<sup>2</sup> on the building's roof, having an optimum slope of 30° to 45°. The technical aspects to be considered are the following:

Maximum Power=250w; Short-circuit current=8.93 A and Maximum Voltage=29.81 V

## Conclusion

The programme description, urban landscape settings, the building's position in the plot and the resources economy, allow to see the determining criteria for the project's sustainability. The material-construction stage aspects, the chosen technology, the method used and materialisation, stand out as being compatible with the environmentally friendly purposes. This material and formal elements combination's behaviour, have an optimum result regarding its energetic efficiency.

From this analysis we arrive to the conclusion that the juxtaposition between the chosen material systems and the relevance of its construction techniques, create certain tension regarding current sustainability correction criteria.

## Bibliography

- Abalos, I; Sentkiewicz, ; (2015). *Essays on Thermodynamics, Architecture and Beauty*. Ed. Actar Publishers. New York
- Banham, R. (1981) *The Crystal Paradise*. Originally in Architectural Review, February 1959. En Design By Choice, Articles compilation by Architectural Design, Academy Editions, 1981, pages 29-33. Translated by Juan Ignacio Azpiazu, [www.ignacioazpiazu.com](http://www.ignacioazpiazu.com).
- Banham, R. (1975) *The Architecture of a Properly Conditioned Interior Space*. Ed. Infinto. Bs. As.
- Esteves A., Gelardi D., Oliva A. *The Shape in the Bioclimatic Architecture: The FAEP Factor- Proceedings II Teachers Conference in Architecture*, Florencia, Italia, cap. 3.12. 1997.
- García-German, Javier (ed.); 2010. From Mechanics to Thermodynamics. *Defining Architecture and Territory from the point of view of energy*. Editor: Javier García-German. Ed. Gustavo Gili. Barcelona.
- Gelardi, Daniel; Esteves, Alfredo; Teaching the *Role of the Construction Techniques. Cognitive aspects relevant to environmentally friendly construction as an optimun tectonic potential in contemporary building*. Chapter III of the Latin American Conference: Introduction to Architecture Teaching. Strategies for a thorough training. 12th to 14th November, 2014. Mendoza, Argentina.
- Piñón, H. (2009) *Project means Construction*. <http://helio-pinon.org/>
- Sloterdijk, P. (2004) *Spheres II. Globes: Macrospherology. Cap. Air conditioning (p= 873-881)* Ed. Siruela. Biblioteca de Ensayo. Madrid.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## RED on RED

### A Framework for the Interaction of Color in the Build Environment

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**Abstract:** This project is based on a proposal for a temporary experimental installation for the International Garden Festival at Les Jardins de Métis in Grand-Métis, Quebec, Canada. Building upon Josef Albers's seminal primer on color theory, *Interaction of Color* (Yale, 1963), the garden project was designed to establish a new framework for experiencing and testing color perception and sensation in a larger field. *Interaction of Color* is valuable architecturally, aesthetically, and in terms of performance. The effect of color can be increased without changing people's perceptions of the color in a space by understanding the interaction of color with the larger built environment in nature or within larger fields. The proposed research project focuses on the connection between design principles and color interaction in order to develop our understanding of how to optimize spatial efficiency, performance, and visual comfort. This research also explores the potential.

**Keywords:** Colorreflectivity, Color Experimental Spaces; Color Perception and Performance

#### Introduction. Initial Garden Project

This research project is based on a proposal for a temporary experimental installation for the International Garden Festival at Les Jardins de Métis in Grand-Métis, Quebec, Canada. Building upon Josef Albers's seminal primer on color theory, *Interaction of Color* [1], the garden project was designed to establish a new framework for experiencing and testing color perception and sensation in a larger field (Figure 1). The proposed garden installation measures 10x20 meters and is surrounded by an open perimeter fence, with entrances located at the east and west ends. Inside are seven walls or fences that organize the plan into eight equal bands, each measuring 2.5x10 meters. Breaks in these interior fences delineate larger spaces and allow for numerous pathways through the enclosed garden (Figure 2). Countering the geometric rigor, the breaks in the fences filter visitors through the garden, loosely defining larger spaces and providing entry points on the east and west sides along the main pathways. Continuous beds of thyme are planted along the organizing bands and are crossed over by visitors (Figure 4).

All the fences are made of painted wood and are characterized by fine slats oriented at 45 degrees and -45 degrees, alternating orientation at each layer. The diagonal slats of the open walls in the garden alternate at each layer, resulting in a series of spaces of intensifying color and opacity at eye level. Recalling the common wooden lattice, these diagonals establish a decidedly supergraphic element in the garden project.



Figure 1: "Red on Red" Garden Entrance Elevation

The artificial tectonic expression serves to abstract the modest methods of construction and articulates a complex set of color effects through minimal means. The perceptual dimensions of color were selected on the basis of contrast and an interest in interaction, participation, and exchange. A range of reds was selected for high contrast with the greens of the surrounding forest and garden plantings, underscoring the contrast between natural forms and the graphic tectonic. The perimeter fence is a pure red. The other fences are painted varying red hues, some of which are tinted (white added), others toned (black added). Since colors of equal brightness but differing hues tend to assume the same spatial plane, the three-dimensional organization of the garden is at times challenged, and an element of spatial ambiguity is introduced. The specifications of the reds used were based on my previously conducted experiments on color reflectivity. These experiments suggest that although our aesthetic valuing of deep colors often conflicts with the high reflectivity that is more effective for daylighting, the average reflectivity of an interior space can be increased without changing people's perceptions of the color in the space. The experiments were conducted using color models of rooms to compare subjects' perceptions of colors and reflectivity to actual measured reflectivity.

### The Colorfulness of Color

Another previous experiment that pertains to this project was conducted to test people's perception of colorfulness. Colorfulness and chroma are described by Mark Fairchild (Wiley, 2005) as comprising one dimension of color (the others being hue and brightness/lightness). In his description, "Colorfulness is to chroma as brightness is to lightness...Colorfulness describes the intensity of the hue in a given color stimulus. Thus, achromatic colors exhibit zero colorfulness and chroma, and as the amount of color content increases (with constant brightness/lightness and hue), colorfulness and chroma increase." Colorfulness is the "attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic." Chroma is the "colorfulness of an area judged as a proportion of the brightness of the similarly illuminated area that appears white or highly transmitting."

My experiment on colorfulness looked at techniques that have been used architecturally, such as reflective surfaces. I used a set of experimental measurements to test anecdotal knowledge about the perception of color in space. Seven identical boxes, or models, were built out of black foam board so that no light could go through the edges.

The inside was covered in white for high reflectivity. Each box was 20 x 20 centimeter in plan and 20 x 20 cm in elevation. One side had a central opening: a 5 cm square aperture, called the “window.” On the opposite side was a central viewport of half an inch diameter. The window side, with the 5x5cm opening was colored in a range of 8 different commercial colors, varying in Light Reflectivity Values from 0% to 99%. The colors are listed, along with their LRVs (percentages): Exotic Pink 68,3% Flamingo’s Dream 40,2%, Calypso Orange 37,8%, Red 11,7%, Strawberry Red 14,2%, Red 13,2%, Raspberry Truffle 8,5%, Chestnut 7,2%.

In these experiments 50 participants were tested for their perceptions of colors. The boxes, each with different shades of red on the inside surface on the wall with the window, were observed in varying stages of light. Observations were made at a distance of 5 to 6 feet, monocularly. In a frontal and parallel position, each human subject tested placed the box in front of her/his face, with her/his eye tight against the viewport, looked through the ports of the boxes, and described their perceptions of each color at three different light levels:

a) bright (a light source), b) not so bright (a white wall), and c) the transition between them (a gray wall). The questions asked were: Which is the most colorful wall? Which is the most colorful box? Despite the actual performance of the Light Reflectivity Value in the color range of eight shades of red, the boxes with the “Flamingo’s Dream (LRV 40.2%) and Calypso Orange” (LRV 37.8%)” were perceived by most of the observers to be the most colorful. It proofs that the most colorful colors are not necessarily the darkest ones. This result contradicts the assumption that colors with the lowest reflectivity values are the most colorful.

A follow-up experiment, The Appearance of the Color Red, was conducted. Mark Fairchild (Wiley, 2005) writes in “Color Appearance Terminology”: “While color is typically thought of as three-dimensional and color matches can be specified by just three numbers, it turns out that three dimensions are not enough to completely specify color appearance. In fact, five perceptual dimensions are required for a complete specification of color appearance: Brightness, Lightness, Colorfulness, Chroma, Hue.” In this second experiment on the appearance of red, I built a series of boxes, or models of rooms, to address the question of reflectivity with changing room configurations. Each of the boxes represents a room with a window on one side, as described in the previous experiment. One set of boxes had the color at the window side; another set of boxes had the color on all fives sides except the window side. The project was designed to study the relationship between the amount (size) of color—and its location and reflectivity—and the human perception of it, along two variables: How the daylight factor changes under the same light The boxes provided a limited point of view. Participants could not see the whole space; they could only see the opposite wall with the window and a quarter of the neighboring walls. The experiment showed that the Average Room Reflectivity (ARR) changes very little within the range of colors from an LRV of 7% to 68 % if only one wall is colored. But the ARR changes dramatically when all five sides are colored. The question asked was: Which is the most colorful room? Each version of the boxes tested (1 wall colored or 5 walls colored) showed the same result, which indicates how important the field of view is and that controlling the view is a way to make a space appear colorful. These experiments showed that the eye is capable of making separate judgments about color reflectivity, and therefore the results provide a point of departure for the selection of color for the garden project: That the most colorful colors are not necessarily the darkest ones (Figure 2).

How do these findings translate to an exterior space? The results of this red viewing test based upon 50 participants were discussed and used to determine the selection of the

different reds and their positions in the garden project. This experiment showed that the eye is capable of making separate judgments describing color appearance and perception.

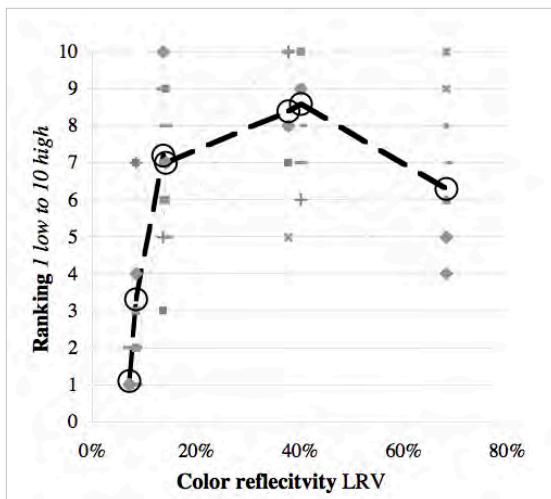


Figure 2: Observers perceived a room to be the most colorful when it was in the reflectivity range of 30-40%.

Therefore the 8 different reds used under the same set of viewing conditions (indoors and outdoors) including reds with significantly different light reflectance values, yet same size, texture, sample type and set-up, have been used for the garden project. It was found that human subjects' results are with little difference or similar to the tested performance of the reds to the empirically location of the colored fences in the garden project. The reds with a LRV 40%-60% have been perceived with the strongest interaction of color in the garden project. With the garden-project we understood that the interaction of the painted slats both with each other and with the colors in nature would remain a dynamic condition. By interspersing small areas of color through the slats, the project highlights the relativity of color and serves as a playful manifestation of the Bezold Effect—that a color may appear different depending on its relation to adjacent colors. The garden is an invitation to see and celebrate that interaction on multiple fronts (Figure 5).

### Garden Project Revisited and Expanded

Using the initial garden proposal as a point of departure, this project delves into the history of color experiments focusing on visual perception and the analysis of color, intensity, flicker and ambience within larger fields of interaction. The objective of this research project is to study, test, and evaluate a series of multiple and complex visual effects as they occur in the built environment and in nature. The project aims to expand upon Albers's color experiments in this larger field and to examine the potency of his discoveries outside of his regulated and abstract color experiments. To what degree do the experiments in *Interaction of Color* translate to architectural spaces— both interior and exterior? What are the limits of these color effects? What is their potential in larger and more complex fields?

Hypothesis: Interaction of Color is invaluable in aesthetic, architectural, and performative terms. Our research project focuses on the connection between design principles and color interaction in order to develop a better understanding of how to optimize spatial efficiency, performance, and visual comfort. This research also explores the potential for using colors to expand, confuse, conceal, and misrepresent built three-dimensional forms.

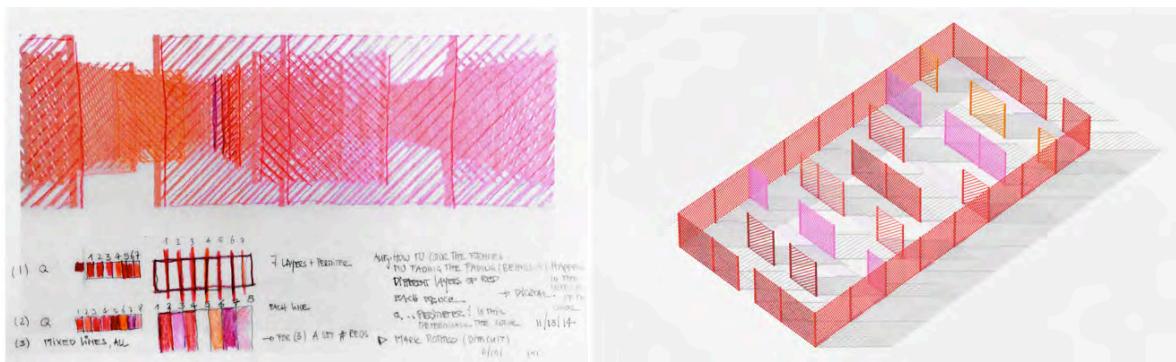


Figure 3 and Figure 5: "Red On Red" Sketch Color Pencil. Concept Axonometric

The effects of color interaction in architecture are neither widely applied nor understood in the field. The color experiments, observations, discoveries and explanations of Joseph Albers represent an untapped potential to further expand our knowledge about color interaction as more variables are introduced. To test the hypothesis, the perception of color interaction will be assessed empirically. The proposed subsequent studies and iterations will largely maintain the existing formal strategy and will focus primarily on the effects of color and reflectivity, understanding the interaction of the painted slats, both with each other and with the colors in nature, which are in a constant state of flux over the course of the day and seasons of the year, as a dynamic condition. This project asks similar questions to those of Albers: What colors recede? What colors advance? What colors appear to share the same spatial plane? The study will seek to amplify the relativity of color: that a color may appear different depending on its relation to adjacent colors. How does color interact outside of Albers's two-dimensional color experiments? What is the dimension of color in space? We anticipate comparable results of color interaction, and will test the interaction of color in space through a battery of empirical tests within a structured exterior construction (Figure 3). The research projects developed a series of scale physical models in order to test the interaction of color within larger spaces and environments. The models explore color interaction by using a range of graphic techniques to maximize the relative appearance of a color in relation to adjacent colors when these fields are interspersed.

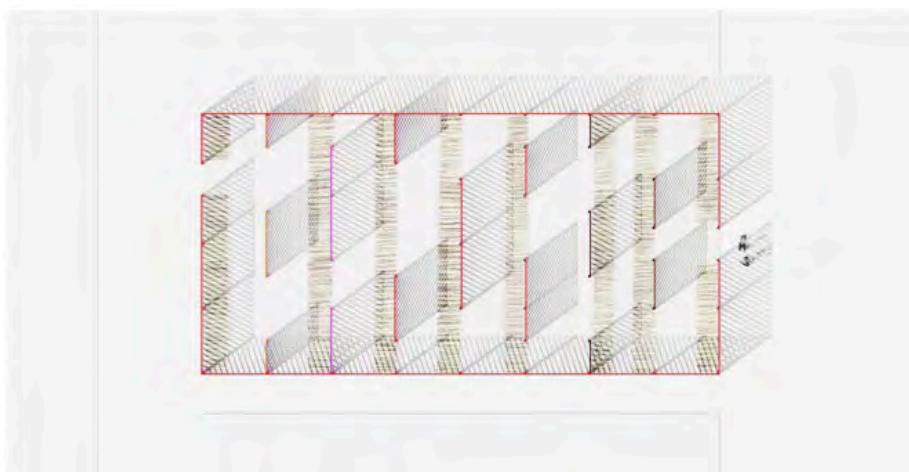


Figure 4: "Red On Red" Garden Plan

#### Guiding Research Questions and Experiments:

- Can we achieve the perception of intense colors while also providing little color?

- How can space be colorful without using too much color? Moreover, what is the minimum required?
- What is a strategy for color interaction in nature—with the plants, the sky, the seasons?
- How do we apply the *Interaction of Color* to conditions that are in a constant state of flux?
- Building on El Lissitzky and Theo van Doesberg, are there other ways to challenge the primacy of spatial form?
- In what ways can the use of color alter or deny three-dimensional space?
- Can spatial composition and color be at once independent and dependent systems?
- How can one minimize and/or maximize the optical destruction of volumes and forms in space? What are the fundamental techniques?
- What are the potentials of the Liebermann effect—where two colors that are of equal brightness but differing in hue assume the same spatial plane?
- What are the ways that built forms can generate the atmospheric effects of a Seurat painting? How can the viewer assimilate colored elements?

### **Evaluation of Reflectivity: The Experimental Garden**

These effects will be investigated in a larger context of variables, including daylight, shadow, background conditions and colors (seasons and plants), and the position of the viewer. The following issues will serve as key points of investigation:

- The outline and definition of space through color.
- The undermining of architectural space through color application.
- Spatial effects of color, including compression, extension and resolution of volumes.
- Connection and disconnection of spatial elements by color.
- Contrast effect of color especially in outdoor and/or daylit spaces.
- Experimental measurements to test anecdotal knowledge about the perception of color in space.

### **The Experiments**

The initial proposal for the “Red on Red” Garden was an experiment designed to observe how color interacts in an outside landscape. Special attention was given to background, horizontal and vertical vantage points, and changing light conditions. Further experiments are based on the planometric geometry of the initial garden proposal—a 10 x 20 meter area surrounded by an open perimeter fence and subdivided by a series of open fences into eight equal bands, each measuring 2.5 x 10 meters. In the experiments, several variables were introduced: color, reflectivity, ordering, height, density of the slats, time of day, time of year, and the relative position of the various viewers.

A set of 8 colors may be assigned to the garden: 1 color for the perimeter condition and 7 colors for the seven interior fences, whereby each plane of the project has a specific color assignment. The colors may be matte or glossy (varying degrees of reflectivity). The assignment of colors and their sequential order could be reorganized. While the regulating plan geometry was fixed, the position and site of the openings that allow people to pass through the garden could be changed. All fences, however, would remain equally spaced at 2.5 m and be parallel with each other and perpendicular to the viewer and direction of

movement. The overall structural support positions would remain, but the height of the garden walls could be increased up to +1m or reduced up to -.5m from the original 2.5m above the ground plane. For each of the experiments the height of the fences is constant in each configuration. Depending on the eye height of the viewer and the height of the fences, the illusion of spatial advancing, or spatial receding, could be reinforced. The parallel fences form a series of vertical and horizontal transparent planes. If the planes of color generated by the fences form a series of concentric rectangular planes of color, the spatial effects are reduced to a minimum. In the case of the initial garden proposal, given an average eye height of approximately 1.57m and a fence height of 2.5m, the color sequence appears to advance counter to its plan metric organization or spatial ordering generated by the colors because of the larger areas of color that appear in perspective on the lower boarders.<sup>1</sup> The dimensions of the individual diagonal slats that comprise the series of parallel fences remain constant. Similar to the original garden proposal, the slats are always oriented at 45 degrees and -45 degrees, alternating orientation at each layer. The spacing of these slats, however, can either be doubled or reduced to half the dimension of the original garden proposal for each wall. The effects produced are known as the von Bezold Spreading Effect (sometimes referred to as spatial color mixing), which is facilitated by the alternating direction of the slats as well as the staggered positioning of the openings in the fences.

Additional variables in the experiments are environmental and perceptual in nature. The time of day was examined for the summer and winter solstice, as well as the autumn and spring equinox—both in direct sunlight and under a cloudy sky. The garden was re-oriented from its original position so that one of the entries faced north. Similarly, the surrounding forest, garden, and sky color reflected typical seasonal and daytime changes. Because these environmental inputs frame the color experiment of the colored fences, the vertical, horizontal, and diagonal boundaries between colors and fields of perceived color may be either strengthened or softened depending on the hardness or level of contrast with the skydome and surrounding vegetation, based on the weather and time of day and year.

Cinematic studies involving a series of stills moving though the various test gardens were developed for each of these conditions (time of day, year). Views were methodically recorded at eye level starting at one entry (moving south to north) and taken at each subsequent fence plane until the other entry was reached. A similar recording was made moving in the opposite direction (from north to south). Records were produced recording these variables, compared and analyzed. Depending on the colors and the order chosen, the garden at times reinforced its own organization, and at other times confounded it. When color and form were in alignment, the garden, or parts of the garden, could be regarded as a functional use of color: color as a means to orient and provide three-dimensional information. However, when the viewer is moving in the opposite direction in the garden, the same colors could have the potential to take on a more de Stijl approach, especially that of Theo Van Doesburg, to confound and disrupt architectural space. In these instances color refuses its typically secondary role in architectural space-making as a decorator or informant.

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<sup>1</sup> The effect of this, as was discovered by Josef Albers and articulated by his student Lois Swirnoff, was "that the illusion of spatial advancing or receding with perceptually mixed colors can be reinforced or diminished by their placement within the vertical/horizontal frame of reference. When seen as concentric groupings, with all intermediate areas appearing equal in size, the spatial effect is diminished. When aligned with unequal amounts of areas or bands of color visible in the upper and lower fields, the perspectival spatial placement reinforced the illusion. With a large area of colors visible along the upper boarders, the groupings seemed to recede in space." p. 44

Here it is not so much the artist playing a subversive or perverse role in the relationship between color and space, but rather the viewer.

## Conclusion

Although these are preliminary experiments and results, the implications were of sufficient interest to continue the work to explain and demonstrate how color can alter our perception of space. Multiple personal tests are being conducted, and we will increase the number of human subjects. These results will be evaluated to establish rules and guidelines for the interaction of color and for color perception in larger fields.

These guidelines will inform design applications for the use of color in architectural spaces and other environments and will be pursued further in a larger experiment. These initial experiments showed that color is much more than a paint or a coating; it is rather a dynamic and highly subjective element. Contrary to its often ascribed secondary role in architecture, color has powerful dimensional potential on par with form itself. These experiments underscore the ongoing significance of Albers's body of work and the continuing relevance of his color experiments.

Architects and designers underestimate colors and their dimension in the built environment and cannot understand the special quality and characteristics of color and color combinations by looking at colors in isolation or without a larger context and field of color interaction. The implications from the results of these experiments are that designers should not rely on their intuition but need tools to apply color and its interaction in all kinds of spaces: interior architecture, architecture, landscape architecture and urban planning. We see this as it is presented as both an ongoing research competition entry and a broader more general research project on the theme of color and form in architecture.

## References

- Albers, Josef (1963) *Interaction of Color*. New Haven: Yale.
- Batchelor, David. (2000). *Chromophobia*. London: Reaktion.
- Behnisch, Guenter. (1993). *Ueber das Farbliche/On Color*. Stuttgart: Hatj.
- Brown, G.Z., De Kay, Mark. (1985). *Sun, Wind & Light*. New York: Wiley.
- Fairchild, Mark D. (2005) *Color Appearance Models*. New York: Wiley.
- Hopkinson, R.(1963). *Architectural Physics; Lighting*. London: Her Majesty's Stationery.
- Hopkinson, R. (1966). Peterbridge, P, Longmore, J. *Daylighting*. London: Heinemann.
- Fairchild, Mark D. (2005). *Color Appearance Models*. New York: Wiley.
- Swirnoff, Lois. (1988). *Dimensional Color* Boston; Basel: Birkhaeuser.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Theory and Precedent in the Design of Sustainable Environments: A Case Study of Two Schools of Art – Manchester and Glasgow

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**Abstract:** The design of a modern building, not least a building that seeks to achieve the greatest efficiency in its environmental design, is substantially a matter of quantification and computation. Design objectives for environmental performance are stated numerically and are assessed using tools such as computer models. But the analytical tools of building science do not directly inform the initial design idea for a building. This frequently derives from reference to *precedent*. This paper presents an analysis of two recently completed designs for schools of art, at Manchester by Feilden Clegg Bradley Studios and at Glasgow by Steven Holl and, in which the architects adopt distinctive approaches to environmental precedent. As background the paper illustrates the significant 19<sup>th</sup> century art school designs in each city, by G.T. Redmayne and Charles Rennie Mackintosh respectively.

**Keywords:** Theory, Design, Precedent, Environment

### Introduction

In a previous paper (Hawkes, 1996a) it was argued that precedent, reference to previous examples of a building type, plays a fundamental role in the development of designs in architecture. Using the example of auditorium buildings it was shown that, even following the development of the modern science of architectural acoustics, precedent continued to be the principal influence on the initiation of a design idea. This paper further examines this proposition in the relation to the design of sustainable environments in modern buildings by considering the design of two recent buildings for schools of art at Manchester and Glasgow. In each case reference is made to the influence of major 19<sup>th</sup> century buildings on their respective modern counterparts.

The original building for the School of Art at Manchester, designed by G.T. Redmayne, was completed in 1881. In 1893 a deputation appointed to write the brief for the new School of Art at Glasgow visited the building. That building, designed by Charles Rennie Mackintosh, was completed in 1910 and is acknowledged to be the masterpiece of its architect. Environmental factors were central to the design of both buildings (Lawrence, 2014a).

Common to each was the priority given to the design of painting studios, where the emphasis was on the quantity and quality of natural light. But, of equal importance, was the attention paid to the design of the thermal environment in which advanced mechanical systems were adopted and integrated into the physical fabric of the buildings. In the first years of the 21<sup>st</sup> century these two institutions have built major new additions to their

campuses. At Manchester by British architects Feilden Clegg Bradley Studios (FCBS) and at Glasgow by New York architect Steven Holl, with JM Architects, Glasgow. It is an intriguing and instructive exercise to draw comparisons between these and their respective 19<sup>th</sup> century predecessors. The following description and analysis places particular emphasis on questions of environmental design and sustainability and explores the relationship between the new buildings and their neighbouring, historic precedents.



Figure 1. Four Art Schools. Left to right: Manchester (1881, 2014); Glasgow (1910, 2014).

### Description: 19<sup>th</sup> century buildings

#### *Manchester School of Art*

Redmayne's Manchester School of Art is on the south side of All Saints Gardens. Its austere, north-facing, symmetrical yellow sandstone Venetian façade is a late example of gothic revival. Behind the façade, however, is a remarkably functional response to the 'cold, foggy and dark climate' of the 19<sup>th</sup> century city, 'its disagreeable qualities much heightened by excessive smoke' (Manchester School of Art, 1874).

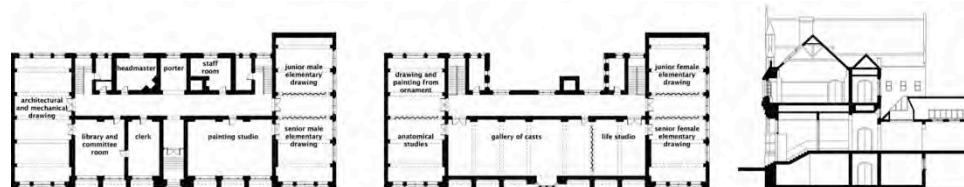


Figure 2. Manchester School of Art. Left to right: Ground Floor Plan, First Floor Plan, Cross Section looking east.

The plan is broadly symmetrical with a centrally located entrance. A corridor runs the length of the building connecting two large studios in east and west wings, with staircases rising up to the main studio floor and down to the workshops lit from lights to the pavement. The main Gallery of Casts on first floor (the principal drawing studio) is lit by a large skylight disguised behind the parapet in the north pitch of the roof. This feature is a development of official guidance, which stated windows should be at 'a height above the floor equal to  $\frac{3}{4}$  the depth of the room, or if the pitch of the roof be steeper than 60°, a skylight should be made in conjunction of the window, so as to gain the same effect in lighting' (Department of Science and Art, 1888).

The quality of the interior environment is controlled by a displacement ventilation system, with inlet grates set in the floor, and outlets through the spine wall to a plenum running the length of the building to a large chimney located to one side of the entrance at the rear of the building.

### **Glasgow School of Art**

The Glasgow School of Art was constructed in two phases, the eastern portion between 1897 and 1899, and the western portion between 1907 and 1910. The orientation of the building takes full advantage of the northern aspect of the site on Renfrew Street.

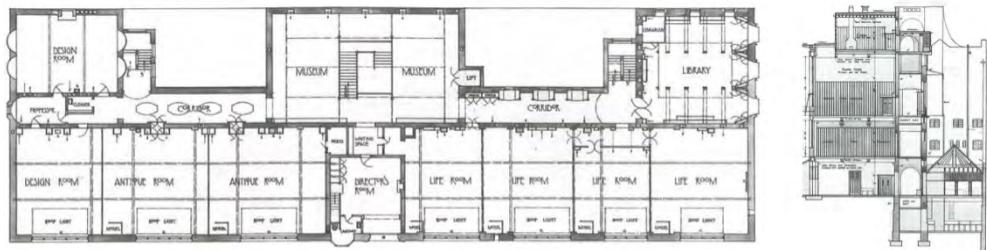


Figure 3. Glasgow School of Art. Left: First Floor Plan; Right: Cross section looking east.

The layout of the environmental systems, an evolution of those installed in Manchester, mirrors the organisation of the plan of the school, with a fan room located directly underneath the main entrance drawing air over heating coils into the main plenum which runs underneath the length of the basement corridor. Ducts rise up vertically from this plenum feeding the studio spaces and corridors to either side of the spine wall, which serves as the thermal ‘hearth’ of the building in section, dividing north-facing studios from the library, museum, workshops and other circulation spaces to the south. Contemporary testing of the school reveals the fine-tuning that was conducted to ensure that this sophisticated system was adequately warming the spaces located furthest away from the fan room. The heating engineers reported that the system exceeded expectations, with internal temperatures in the studios around 60-61°F [16°C], given external temperatures between 41-48°F [5-9°C]. (Lawrence, 2014b).

### **Description: 21<sup>st</sup> century buildings**

#### **Manchester School of Art**

Feilden Clegg Bradley Studios (FCBS) was founded in 1978. From the outset a priority was to develop “an environmental approach to architecture” (Clegg, 2007). Over almost 40 years they have produced a body of work in which the meaning of this term has been extensively explored. In a review of the work of the practice one of the present authors (Hawkes, 2007b) proposed that, “each design exhibits the ‘discipline’ that comes from the application of environmental principle, given expression through clarity of form and directness of detail.” It was suggested that, in this respect, the work represented an environmental development of the ‘Functional Tradition’, proposed by the British critic J.M. Richards (Richards, 1958), in which buildings, by their, “expressive use of materials ... display ... the essential attributes of architecture.”

The new building for Manchester School of Art, by FCBS, the Benzie Building, is located to the south-west of Redmayne’s building. It incorporates a 1960s extension with a 9-storey tower above a 3-storey podium. The new building is a 4-storey, deep-plan rectangle to the west of this. Topographically the plan is clear. The entire north, a glassy vestibule, dubbed the ‘living room’, occupies the entrance front. Behind this lies the working part of the building, ‘the factory’. At the heart of this, a stepped, top-lit atrium is criss-crossed by staircases and surrounded by four floors of studios and workshops. The building has an

insitu concrete frame, an inheritor of Le Corbusier's 'Domino' frame. This is clearly expressed throughout the interior. The exterior is clad in anodised aluminium panels that alternate with vertical strips of glazing.

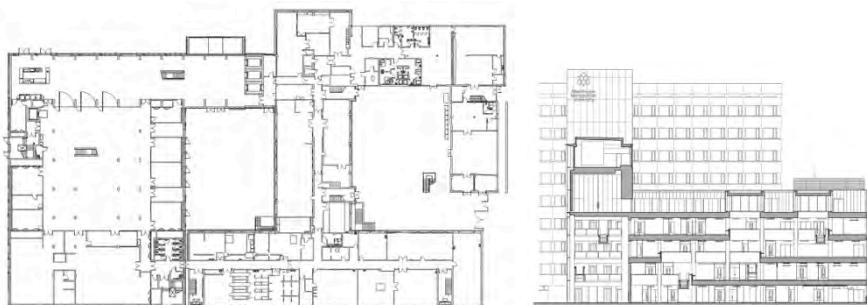


Figure 4. Manchester School of Art. Left: Ground Floor Plan; Right: Cross Section looking east.

Writing about the early work of FCBS, Hawkes (Hawkes, 2007b) identified three consistent principles that informed their environmentalism: *orientation*, *cross-section* and *envelope*. These factors, whilst still identifiable, are here less influential, both formally and environmentally. *Orientation* is acknowledged in the southerly stepping of the atrium of the 'factory' and it is here that the concern with the *cross-section* is most clearly registered. It is with the *envelope* that the design most apparently departs from earlier practice. Here we have a curtain wall, identical on east, west and south façades, with alternating panels of glass and aluminium. The north, entrance façade is a six-storey skin of mirrored glass, differentiated by annodised aluminium fins at high level.



Figure 5. Manchester School of Art. Photographs showing transitional spaces. All 1/30 sec at f/3.5, ISO 200.

A single storey porch entered centrally through automated double doors articulates the entrance to the building. This provides an air-lock before the entrance to the circulation hall itself. This light-filled space is photogenic and has become the social centre of the building, justifying its designation as the 'living room' (figure 5, top left). Beyond the 'factory' is more utilitarian and presents a gradual transition into dimmer spaces that are more and more closed off from the outside world, with daylight replaced by the uniformity of energy efficient lighting calibrated to provide precise lumen levels upon detection of occupancy. This artificial light is provided by cylindrical metal lamp fittings set in the concrete slab and

fluorescent tubes set into the suspended acoustic panels that line the ceiling of all the balconies and studios.

The thermal environment is controlled by a combination of air-handling units with underfloor heating. The system provides different volumes of air according to occupancy levels in different spaces, and recovers heat from the air for use in cold weather. It can also supply recirculated air in conditions of low occupancy. A 2015 post-occupancy survey (Pendergast, 2015) indicates that temperatures are considered too hot in both winter and summer (mean scores of 5.00 and 5.63 on a scale from 1: too cold – 7: too hot, which translates into an average score of +1.32 on the ASHRAE Thermal Sensation Scale). 59% of respondents reported no control over ventilation, and 37% reported that the temperature has a negative impact on their work. This suggests that the internal temperature as controlled by the Building Management System may not reflect seasonal variation in external conditions, leading to discomfort, as users are more conscious of their adaptation to the internal environment. The survey records that annual energy use (including both the new building and the refurbished tower) is around 191kWh/m<sup>2</sup>.

### **Glasgow School of Art**

In 2009 Steven Holl won the competition to build a new building for the Glasgow School of Art. The Reid Building, executed in collaboration with JM Architects Glasgow, was completed in 2014. The site is directly opposite Mackintosh's original building and it is appropriate to discuss Holl's design in relation to that. The ground plans of the two buildings show their broad similarity. Each is a clear-cut rectangle with relatively simple spatial organisation. It is the cross-section that is the key. In both designs the dominant factor is the priority given to the north orientation of the main teaching spaces. For Mackintosh the windows of the north-lit painting studios are the dominant element of the main façade, but for Holl the faceted glass of the studio elevation fronts a lane to the rear. Mackintosh's plan is divided by a masonry spine wall that directs the main horizontal circulation of the building. To the south of this lie a variety spaces, small and large, whose uses positively enjoy direct sunlight from the south. Holl follows a similar principle, although now the spine wall is replaced by a complex void that divides the building into north and south zones and through which runs a sinuous circulation route.

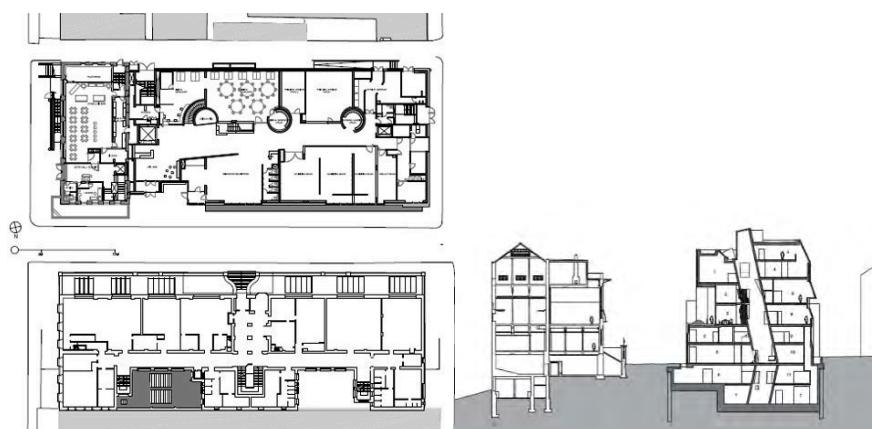


Figure 6. Glasgow School of Art. Mackintosh and Holl Buildings. Left: Ground Floor Plans; Right: Cross Sections looking west.

The structure of the building consists of in-situ concrete load-bearing cross-walls that support the floor slabs. The external envelope is also of in-situ concrete, but clad in a taugh

glass skin, translucent over solid walls with an over-cladding of thermal insulation and transparent at openings. Prominent elements of the building are the three 'driven voids' that cut through and animate the central circulation space from basement to top, maximising the penetration of natural light deep into the building.



Figure 7. Glasgow School of Art. Photographs showing circulation space. All 1/30 sec at f/3.5, ISO 200.

The environmental strategy of the building is summarised in Fig. 8. This illustrates the adoption of a series of principles that contribute to both the environmental quality of the interior and to economy in its operation. These include the use of exposed thermal mass in the ceilings, high performance glazing and building lighting controls. The 'driven voids' are used to facilitate stack ventilation throughout the building. A new biomass boiler jointly serves this and the Mackintosh building. Other features are storm water harvesting and accessible areas of green landscape.

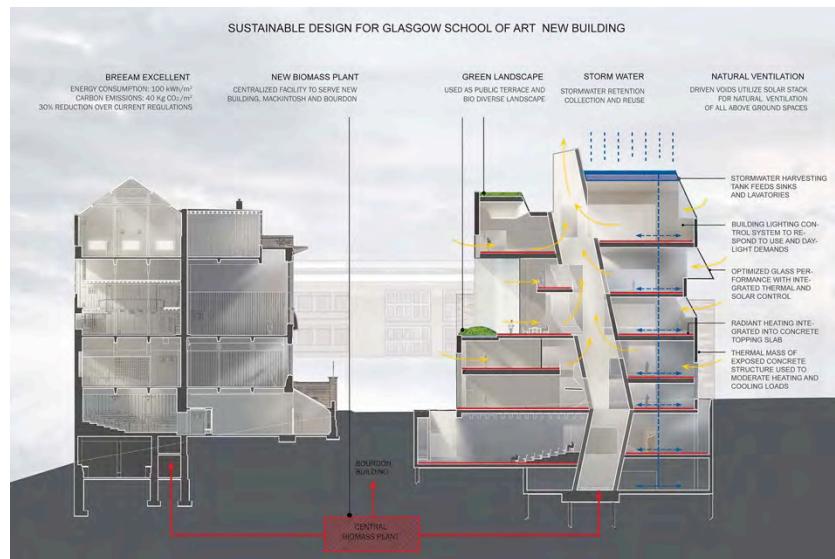


Figure 8. Glasgow Sustainable Design.

A survey of 72 students conducted by one of the authors in the new building indicated that students found the building to be on average slightly warm (+0.76 on the ASHRAE Thermal Sensation Scale), but when questioned about their thermal preference they desired little or no change to the temperature (+0.25). This shows that mechanical servicing does

not necessarily equate to improved occupant comfort, and, furthermore, that the capacity for users to control and to fine-tune environmental conditions in different spaces afforded by a more passive strategy (such as in the Reid building) can provide more opportunities for occupants to adapt to their internal environment in different seasons. Annual energy use in the Reid building is around 182kWh/m<sup>2</sup>. (Stewart, 2017)



Figure 9. Lighting conditions in new studio spaces in Manchester and Glasgow. Both 1/30 sec at f/3.5, ISO 200.

## Discussion

In the 19<sup>th</sup> century the ‘purpose-built’ art school was a new building type. But, as we have shown, the designs at Manchester and Glasgow rested upon well-established conventions of architectural composition, of symmetry and style that informed the new urban building types of the time. Environmentally, whilst both buildings incorporated ‘advanced’ systems of warming and ventilation, their form and detail followed from the historic need to design with natural light. In other words, the design of these ‘new’ buildings was informed by precedent. We have also shown how the Manchester building became, within ten years of its completion, a direct reference – a *precedent* – for the Glasgow building. A century later much has changed. Architecture has experienced the paradigm shift of the Modern Movement and, within this and, perhaps, as a consequence, the basis of environmental design has been transformed in its priorities, method and technology. In addition to providing good physical environments in buildings we now have the obligation to minimise the impact of buildings on the local and global climate. Environmental requirements are now defined quantitatively and design proposals are assessed using sophisticated computer models. Building materials and environmental technologies have changed out of recognition.

The two new art school buildings studied here are quite different in conception. At Manchester the building by FCBS is, in form, material and technology, demonstrably of its time. It may be placed in the lineage of the practice’s earlier work, with its environmental emphasis and acknowledgement of the influence of the ‘Functional Tradition’ and its legacy in the Modern Movement. Its relationship to its 19<sup>th</sup> century predecessor is, perhaps, quite remote. Steven Holl’s Glasgow building is also of its time, as is declared by its initially startling appearance, behind which we find advanced constructional methods and services systems. But the influence of Mackintosh’s building across the street is powerfully present, not least in environmental matters. This is shown in the cross sections, where both buildings adopt the same principles of orientation in determining the disposition of spaces and in providing daylight throughout the building. Our comparative studies show that both new buildings achieve a high standard of energy efficiency. In their environmental intentions, however, they are quite different. The Manchester building, with its clear differentiation of zones, adopts a utilitarian perspective. The social territory, the ‘living room’, is flooded with

daylight from the north-facing floor to ceiling glazing. In contrast, the studio is designated a ‘factory’ in which the environment is a matter of mechanical management and predominantly artificial lighting. At Glasgow the internal environment is more diverse, with a variety of room sizes and types, almost all daylit. A quantitative and qualitative comparison between the buildings may be seen in the images at Figs. 5 & 7.

## Conclusion

Where then does precedent now stand in environmental design practice in architecture? The argument for reference to precedent is that pre-existing designs provide a degree of security in the production of new buildings. They embody principles from which development and innovation may proceed. We suggest that the Reid Building at Glasgow School of Art reveals a deep influence from Mackintosh’s original building. This is not a superficial procedure, but derives from analysis and reinterpretation of the lessons of the earlier building. This is precedent at work. In apparent contrast the Benzie Building at Manchester exhibits no direct reference to such antecedents. Nonetheless it is not free of influence. The ‘Modernist’ frame construction is a convention in contemporary design. More important is the accumulated experience and expertise of FCBS in its 40 years of environmental design practice. This constitutes a body of knowledge that itself acquires the status of precedent.

## References

- Clegg, P. (2007). The Environmental Agenda, in *Feilden Clegg Bradley: the environmental handbook*, London, Right Angle Publishing, pp. 18-21.
- Department of Science and Art (1888). *Directory, with Regulations for Establishing and Conducting Schools of Art*. Document. V+A Archives, London.
- Hawkes, D. (1996a). Precedent and Theory in the Design of Auditoria, in *The Environmental Tradition*, London, E & FN Spon, pp. 56-65.
- Hawkes, D. (2007). Designing with Climate: the principles of sustainable architecture, in *Feilden Clegg Bradley: the environmental handbook*, op cit, pp. 14-17.
- Lawrence, R. (2014a). The Evolution of the Victorian Art School. *Journal of Architecture*, 19, pp. 81–107.
- Lawrence, R. (2014b). The Internal Environment of the Glasgow School of Art by Charles Rennie Mackintosh. *Journal of Construction History*, 29, pp. 99–128.
- Manchester School of Art (1874). *Annual Report*. Document. Manchester School of Art Collection, Manchester Metropolitan University.
- Pendergast, M. (2015). *Post Occupancy Evaluation Report: Art and Design Building, Manchester Metropolitan University*. 8 January 2015. Manchester: Turner & Townsend.
- Richards, J.M. (1958). *The Functional Tradition in Early Industrial Buildings*, London, The Architectural Press.
- Stewart, B. (2017). *Environmental Strategy of the Reid building*. Email to author, 24 March 2017.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Towards a Tropical Architecture: Modernism in Northeast of Brazil

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**Abstract:** The participation of Pernambuco State in the development of the Brazilian Modern Architecture begins from the first stages of the Modernism in the country. In the city of Recife, the debate related to the new architecture falls on a basic theme; the tropical climate. The identity of the architecture should not have only national features but most of all, a regional one. The climate was the principal excuse to support the creation of a new architecture that not only was able to respond to the necessities of a new era, a new time, but also bring climate comfort, which is essential to the life on the tropics. After a heroic beginning, Modern Architecture came to a period where few buildings were constructed, but from the 1950s this all changed. In the following decades there was a clear option for the Modern language for the architecture of Pernambuco State in the hot and humid north of Brazil. The dominating characteristics of Modern Architecture in that state was the experimentation in the creation of formal elements for climate adaptation. Although with distinct formal manifestations, the proximity of the projects methods and the ideology of the architects at work in Pernambuco at the time, indicate similar references. But, to which point these created elements really worked? Were the architects interested in the creation of a tropical modernism? To answer those questions I collected data on 140 buildings constructed between 1950 to the end of 1970s in the city of Recife. I analyzed their formal, thermal and lighting aspects to see if those building conform to the clear views expressed in the Modern tropical speech of the architects of the time.

**Keywords:** Tropical Architecture, Brazil, Recife, Modernism. Final paper upload

### Introduction

The Modern Movement arrived in Brazil at a very significant moment in the country's history, when the discussion around a national identity in architecture was topical. It is quite ironic that at the time the formal modern prototype was received not as a tradition breaking tool, but in fact, as a *tabula rasa* where the fusion of the colonial past with visions of a progressive future could happen (Costa, 1962). Therefore, modern architecture offered a new and acceptably genuine Brazilian tradition divorced from negative imperial symbolism and with a clear vision of having a modern country. The work of Brazilian pioneers such as Lucio Costa and Oscar Niemeyer and the tacit adoption of modern architecture by the Brazilian government finally guaranteed the triumph of modernism as the symbol of a national architecture (Segawa, 1997).

However, the discussions concerning the new architecture in Brazil were more nuanced than one might imagine, and indeed had many different aspects. It was clear that Brazilian architecture at the time did not partake of a single unifying national attribute that was not copied from Europe; being a country of continental dimension there were quite a few identifiable regional features (Berquo, 1998). The modern discussion tended to emphasize the creation of an architecture adapted to the country's climate conditions and, therefore, a real identity-related solution for Brazilian architecture (Bruand, 1981). The problem then

became the identification of this national climate. The reality is that the climate throughout the year in the various regions of Brazil differs greatly (Frota & Schiffer, 1998). If an architectural pattern seems appropriate for the cities of Rio de Janeiro or São Paulo, could it be right for a region such as the Amazon, or for Brazil's Northeast coast, where humidity and heat are so much higher?

The intention of this paper is to discuss a type of architecture created in and for the city of Recife, which represents the model built in the northeast of Brazil from the 1950s to the late 1970s. With reference to this subject and relevant to this paper, the main, and most intriguing aspect is whether the architects were justified in creating a School of Architecture with a distinguished style based on responding to the climate (Abreu e Lima, 2000).

### **The Climate in the Northeast of Brazil**

In order to understand the issue at hand it becomes necessary to first discuss the climate of the northeast region of Brazil. Most of the major cities of this region are situated in the bay areas where the climate can easily be defined as Tropical-humid of low latitude (Frota & Schiffer, 1998). Among its many specific characteristics this climate is defined by its high temperature (IDEM).

In this type of climate the temperature does not vary much between night and day nor even between different seasons (Hertz, 1998). This is due to the constant relative humidity found in the air that does not allow for the sun's rays to elevate the temperature in the day time and will not let the elements cool down too rapidly at night. The lack of great fluctuation in temperature over the whole year round is explained by the low latitude and the constant and stable ventilation of the region (IDEM).

Although high temperatures determine the heat sensation in this sort of climate, it is actually the relative humidity of the air that plays the most important role in human perception (Frota & Schiffer, 1998). With high humidity, human sweat cannot evaporate and without a certain amount of evaporation, an uneasy sensation of heat is perceived (IDEM). But if the body is subject to some air movement (ventilation), even with the temperature and the high relative humidity levels, the sweat produced by our bodies is evaporated refreshingly (Hertz, 1998).

Unfortunately, such simple but quite illuminating technical definitions were not known to the architects of Pernambuco in the beginning of the nineteenth century. Still it was common knowledge that European architecture built unchanged, simply did not work in countries with hot and humid climates and that a good architecture was one which made possible effective ventilation of internal spaces (Serra, 1999). With this knowledge, the question became what would the external appearance of this tropical architecture be like?

### **The Brief but Decisive influence of Luis Nunes**

In the 1930s the State government invited a group of young modern architects to run the department of construction of Pernambuco (Vaz, 1989). This was the first public initiative in Brazil related to adopting modernism as a style in architecture for the construction of public buildings and the only one before the federal government of President Getulio Vargas (Baltar, 1951). Luis Nunes was to run the department of construction and his contribution to Brazilian architecture is quite unknown due to his short career; he died rather prematurely (Baltar, 1963). But among his staff were some young professionals whose work became very well known, such as Roberto Burle Marx, who is renowned all over the world for his landscape design, and Joaquim Cardozo, who after the experience he garnered in Recife, became the

chief engineer on key works of Oscar Niemeyer, mainly in projects such as the Pampulha and the Brasilia National Capital (Barros, 1976).

There was no explicit intention of creating an aesthetic language within the buildings they constructed, but rather a cheap and quick-to-build structures with well-ventilated internal ambience (Marinho, 1989). For this purpose, Nunes and his staff trained the laborers in the production of concrete modular structural elements that were to be made at the construction site itself, and were designed in such a way that they could be repeated in many projects so such elements might be reused (Nunes, 1935). The solutions they came up with for ventilating the buildings ended up offering great inspiration to a whole new generation of architects to come. Their impetus and practice of incentivizing the creation of new ways of adapting a building to a tropical climate were particularly influential.

### The Making of a School of Tropical Architecture

After the Luis Nunes experiments, in the 1940s few modernist buildings were raised in Recife, but modernism was very much a palpable presence in Pernambuco.

With the coming of the 1950s modernism became pervasive in Pernambuco architecture. The question of why this became so must be explained by the academic upbringing of the architects who graduated in Recife (Amorim, 2002). The Faculty of Architecture of Pernambuco had four lecturers by the end of the 1940s, three architects and one philosophy teacher, and these academics had a critical influence on a whole generation of professionals. The three architects were the Italian Mario Russo, the Portuguese Delfim Amorim, and Acacio Gil Borsoi, who was from Rio de Janeiro. The three came from a strong modernist background with lengthy careers both as lecturers and architects.

The skyline of the city of Recife was virtually transformed during the 1950s, and this modernist building bonanza was fueled by an economic boom that occurred during that period. At that time, Russo, Amorim and Borsoi were responsible for planning many apartment buildings as well as important government constructions. As lecturers, they taught the basic principles of modern design, and as architects, they would employ a great number of their students as trainees in their offices and later on, as architects (Amorim, 2002). So, the construction site would invariably become a classroom where their teachings were to be put into practice.

Nonetheless, in spite of these three architects having similar modernist backgrounds, each used different methods and had distinct aesthetic influences. The one element that united the three, and that later on would be recognized as the one characteristics of the School of Architecture, was their inventiveness in creating climate adaptation elements. Following the experience of Nunes, the teachers strongly encouraged the continuous creation or re-interpretation of constructive elements which could offer any betterment in the adaptation of buildings to the tropical climate (Borsoi, 1994).



Fig. 1. Wall tiles patterns designed and used by Delfim Amorim, photos by the author

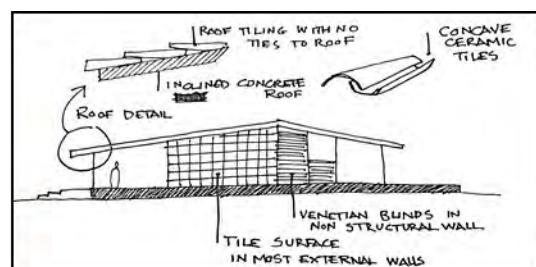


Fig. 2. *Casa tipo* (Type House) by Delfim Amorim, drawing by the author.

Towards that goal, virtually anything was valid, from the use of a different modern architectural vocabulary, via adaptation to the tropical climate, to the reinterpretation of effective solutions from previous architectural styles. An example of this is clear in their use of tiles; their re-interpretation of the use of tiling as an external coating was not something that was in vogue before the 1950s. The Pernambuco architects brought back wall tiling as modern geometric motifs following the Old Portuguese tradition where the same pattern is repeated over and over in the building's façade (Fig.1).

They also re-interpreted the Portuguese-Brazilian traditional colonial roofs. Such a return to traditional roofing was first tried by Delfim Amorim in some housing projects he designed (Amorim, 2002). He came up with a simple solution of a concrete roof just a little tilted, over which the roofing tiles are fixed without any type of wood to hold them in place (Fig.2). This roofing tile design permits the air to travel between the concrete and the tile. Air is not trapped as the tiles are not completely sealed, and in this way there is a constant renewal of air between the concrete and the tile. Although this air movement is not strong enough to move the tiles themselves, it is enough to cool down the roof. With time, this type of roof became so popular and was used on such a scale that it has become one of the major characteristics of the houses in Pernambuco (Amorim, 1999).

Delfim Amorim arrived from Portugal with a strong background in European modernism in which the aesthetics of a building had to follow a clear geometric rigor. It did not take long for Amorim to alter his design method to accommodate the social and economic conditions he found in Brazil, as well as to the climatic conditions of Pernambuco (Amorim, 1988).

With a different approach, the Italian architect Mario Russo understood that the climate condition was just one of the many aspects to be tackled by architecture. Russo was a modernist, not just aesthetically and design-wise, but also ideologically (Cabral, 2001). His buildings followed rational modern principles, searching for answers to the problems faced by the building's design with a detailed study of its functions and necessities (IDEM). His method of design left no space for aesthetic tastes regarding fashion or any type of regionalism. That being said, it is a fact that Russo never departed from the modern flat roof even when a more traditional roof might have been more suitable (Fig.3).

On a curious note, to this day most of the buildings designed by Russo, more than 50 years later are still used without much alteration, such as the examples of the School of Medicine and the University Hospital and it must be said that they still present remarkable thermal and natural lighting conditions.



Fig. 3. Milton Medeiros House, 1956, by Mario Russo, photo by the author

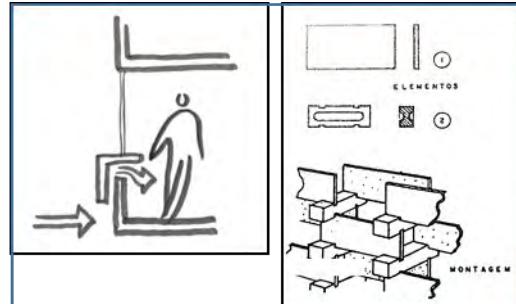


Fig. 4 . 1<sup>st</sup>. drawing: *ventilated sill* created by Augusto Reynaldo and 2<sup>nd</sup> drawing: Acacio Gil Borsoi re-interpretation.

Acácio Gil Borsoi came to Pernambuco from Rio de Janeiro, which at the time was still the national capital of Brazil. His greatest contribution can be found in the development of an architectural design methodology which later would be widely adopted by the majority of architects from Pernambuco (Segawa, 1997). This methodology, though he never called it such, concerned itself with a detailed knowledge of all the components of a given building: its materials and the construction technique to be used, the function of the spaces, of the windows, the doors, even of the hinges (Borsoi, 1961). It is true that his methodology more closely resembled ideological principles found in the *Arts and Crafts* movement than that of the modernists, but as a Brazilian, Borsoi felt that he was free to make his own interpretation of the modernist European movement which he believed, was open to additions and reinterpretations as long as this represented a positive gain to the building (IDEM).

Making use of his detail-specific methodology he systemized the thing that is considered the main characteristic of the architecture of Pernambuco, which is the creativity involved in finding elements for climate adaptation. He was himself responsible for designing various alterations to the *ventilated sill* created by a colleague, Augusto Reynaldo, and to the *cobogos* – a perforated ceramic or concrete block (Fig 4).

In 1963, Borsoi designed one of the most important projects of his career. It was an urban and architectural design for a housing estate made for the Social Organization of the shanty-town of *Cajueiro Seco*, at the time, one of the poorest *favelas* (shanty-towns) in Recife. He proposed a project that was to use local workmanship and a system of construction that was well known to the poorer community, a system called *taipa de pau-a-pique* – lath-and-plaster wall (Borsoi, 1984). This system consisted of the binding of a trellis made of very thin wood that is coated on both sides with clay. Using modern methods of organization and industrialization he modernized the old way of building this type of house turning it into a healthy, quick and cheap construction system. As it was still the same system, the community knew how to use it, so they could build their houses themselves without the need of specialized training (IDEM), (fig. 5). Though aesthetically the houses had no attachment to what is perceived as Modern Architecture, the system in what they were built, the method of assemblage and the possible enlargement of the building were nonetheless based purely in modernistic ideas.

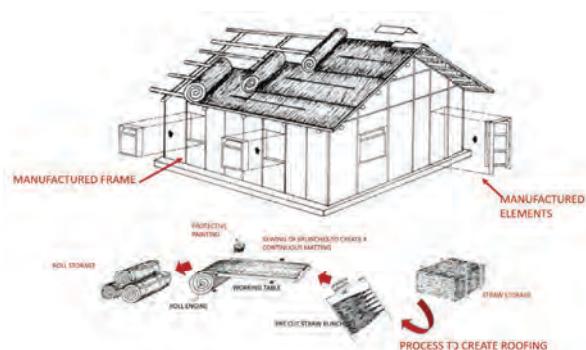


Fig. 5. Cajueiro Seco construction system, by Acaio

Cajueiro Seco became one of the icon examples in Brazil of a cheap alternative to extremely poor conditions that was abandoned by the Government for political reasons. The project, and the architect himself, were considered too left wing for the military dictatorship of the time. The community was abandoned to its original extremely poverty level and some of the land it occupied were sold to private initiative to build hotels.

Nonetheless the ideas Acacio Borsoi, Delfim Amorim and Mario Russo were vital for the creation and the perception of an architecture for Pernambuco by consolidating the ideals of the modern movement with the region's climatic needs (Borsoi, 1994). The aesthetic result of resulting buildings, nevertheless, did not offer much uniformity between them. The one uniform quality that unified them all was their elements of climate adaptation that defined the volumes and the interiority perception. The interior quality of these buildings is acknowledged by the architects of Pernambuco having been directly influenced by another one of the faculty's teachers; he was the Sociologist Evaldo Coutinho.

### The different faces of a single School

Without ever having designed a single building, Evaldo Coutinho had, nonetheless, a most remarkable influence over the architecture of Pernambuco. For him, architecture was the most complex art form and it could not be understood simply as being limited to such physical aspects as walls, sealing, and floors (Coutinho, 1998). A good architectural design had to be related to sensations of wellbeing, where the presence and the idea of beauty was a most fundamental quality (IDEM). This impetus was not related direct to aesthetic taste but to translate itself to fundamental questions, such as the need for and use of natural lighting and human sensual perception of colors and textures, how vegetation played an important part in changing light by diffusing it and generating shadows, and how the proportions of height, width and length impact a person's perception of a given space (IDEM).

Therefore, 'beauty' for Coutinho, was synonymous of a well-adapted building to its climate, where its inhabitants will not feel cold nor heat, but the perfect state of comfort (IDEM). With such principles in mind, the architects went out and would search for the ideal ambience considering the climate of Pernambuco. The use of *brises soleil*, *cobogós* or of any other element of climatic adaptation, does not interfere in the plastic composition, in fact, these elements seem to contribute to the geometrical character of the building.

Other buildings show a greater fusion between the modern form and traditional elements such as venetian blinds, verandas or roof top details. A good example of this type of integration can be found in the "Vila Mariana" Building designed by Wandekolk Tinoco in 1977. The building was designed as a pure white volume following the distinctive language found in the works of Le Corbusier. But here the windows were pushed back 2 metres to give space for gardens on every floor. The intention of the architect was to create internal spaces that were similar to traditional Pernambuco residences, where sight of a vegetation filled garden is the norm. The natural light is naturally diffused by the vegetation and the apartment interiors would feel like the interior of a traditional house (Fig. 6).



Fig. 6. Vila Mariana Build., by W. Tinoco

Another aesthetic tendency of the school of Recife was the design of buildings which deconstructed the pure volume typically found in modern architecture. The nooks and crannies of their volume were justified by the pursuit of greater insolation and ventilation conditions. *Brisas Soleil* were used as elements of adaptation to the climate as well as elements of aesthetic composition, giving a kind of rhythm to the façade of the building.

This pursuit of an adequate architecture for the climate and the specific economic realities of Pernambuco, was to travel many different paths, with degrees of achievement.

## Conclusion

The aesthetic diversity of the modern architecture produced in Pernambuco might lead to the conclusion that there existed many different currents with different attitudes and distinct design justification. However, when research into the generating process of this diversity of forms reveals their unity. This unity is related to the idea of a School of Architecture that shared common characteristics and references and that shepherded a specific type of process of architectural design.

There is no doubt that the union of these characteristics and references in the works of the architects in Pernambuco was the result of a direct influence from their academic upbringing in the Faculty of Architecture of Recife.

The incentive given to aesthetic experiments and the creation of climatic adaptation elements, contributed to a rich stock of solutions. The techniques, building methods and elements created and used by the architects, contributed to the quality and originality of their work. They also had a profound influence on the whole built environment production of the northeast region of Brazil. To this day, anonymous architects and laymen builders make use of these elements of climate adaptation, even though many may do so simply to give some sort of plastic expression to their buildings.

The modern architecture built from the 1950s to the late 1970s produced some remarkable examples of how a modern society can adequately coexist with the heat and humidity of a tropical climate, by reconciling traditional references with modern ones. Although the need to create a Brazilian tropical architecture had been the theme of great debate since the beginning of the twentieth century, it was only with the adoption of modern design that the architects were able to realize their goal. The various aesthetic approaches used by the architects of Pernambuco still permit the recognition of the basic principles that gave unity and quality to the architecture produced in the state's capital. These principles qualify this architecture as the fruit of a school of tropical architecture emanating from the design of the School of Recife.

## References

- Abreu e Lima, Daniele & Silva, Geraldo G. (1997). Armando de Holanda: um arquiteto do nordeste. In: AU n. 69. pp. 67-72.
- Abreu e Lima, Daniele. (2000). Arquitetura Moderna nos Tropicos: Exemplos em Pernambuco. Master Thesis, Faculty of Architecture, University of São Paulo.
- Amorim, Luiz M. E. (1988). Responsabilidade social marca obra de Delfim Amorim. In Projeto n.115, pp 45-47  
\_\_\_\_\_. (1989). Delfim Amorim. Construtor de uma linguagem sintaxe. In: AU n.24, pp. 63-67.  
\_\_\_\_\_. (2001). Uma escola regional? In: AU n.94. pp. 60-69  
\_\_\_\_\_. (2002). Modernismo recifense: uma escola de arquitetura, tres paradigmas e alguns paradoxos. In [www.vitruvius.com.br](http://www.vitruvius.com.br).
- Baltar, Antonio B. (1951). Sobre a Cirurgia Urbana. In: Boletim da Cidade e do Porto do Recife, dez/1950 jan/1951.

- \_\_\_\_\_ (1963). Luis Nunes. In: Arquitetura, n.13.
- Bandeira, Manuel. (1930) A Moderna Arquitetura Brasileira. In A Província, n.4.
- Berquo, Elza (org). (1998). Historia da Vida Privada no Brasil. Sao Paulo: Companhia das Letras.
- Borsoi, Acacio G. (1961). Inqueritos Nacionais de arquitetura – Depoimentos. In: Arquitetura n.1.
- \_\_\_\_\_ (1974) Taipa. Recife: Recife Gráfica.
- \_\_\_\_\_ (1984). Cajueiro Seco: o caminho interrompido da autoconstrucao industrializada. In: Projeto, n. 66.
- Borsoi Associados (1994). Escola do Recife. In: Projeto jan/fev 1994.
- Bruand, Yves. (1981). Aquitetura contemporanea no Brasil. São Paulo: Editora Perspectiva.
- Cabral, Renata C. (2001). Mario Russo, Por uma visao integral da arquitetura. In: AU n.96, pp 55-64.
- Costa, Lucio. (1962). Sobre Arquitetura. Porto Alegre: Centro de Estudantes de Arquitetura.
- Coutinho, Evaldo. (1998). O Espaco da Arquitetura. Sao Paulo: Ed. Perspectiva.
- Cunha, Paulo W.S. (1978). Desempenho Termico de Coberturas em Paises de Clima Quente. Sao Paulo: Edusp.
- Freyre, Gilberto Z. (1961). The Portuguese and the Tropics. Lisbon: Executive Committee for the Commemoration of the Centenary of the Death of the Principe Henry, The Navigator.
- Frota, Anesia B. et ali. (1998). Manual do Conforto Termico. Sao Paulo: Nobel.
- Hertz, John B. (1998). Ecotecnicas em Arquitetura: Como Projetar nos Tropicos Umidos do Brasil. São Paulo: Pioneira.
- Holanda, Armando (1976). Roteiro Para Construir no Nordeste. Recife: Universidade Federalde Pernambuco.
- Lemos, C.A.C. (1978). Cozinhas etc. Sao Paulo: Editora Perspectiva.
- \_\_\_\_\_ (1979). Arquitetura Brasileira. Sao Paulo: Melhoramentos/Edusp.
- Lira, José T. C. (1996). Mocambos e Cidades. Doctoral Thesis, Universidade de São Paulo.
- Marinho, Geraldo. (1989). Luiz Nunes. Vanguarda na periferia. In AU n.21..
- Naslavsky, Guilah. (1998). Modernidade Arquitetonica no Recife – Arte, Tecnica e Arquitetura. Master's Thesis. Universidade de Sao Paulo.
- Nunes, Luis (1935) Uma diretoria de Arquitetura In: Revista da Diretoria de Engenharia, n. 2, V.III
- Segawa, Hugo. (1998). Arquiteturas no Brasil – 1900-1990. São Paulo, Edusp.
- Serra, Rafael. (1999). Arquitectura y Climas. Barcelona: Editorial Gustavo Gili.
- Vaz, Rita C. (1989). Luis Nunes: Arquitetura Moderna em Pernambuco, 1934-1937. Master Thesis, Universidade



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Fifty Shades of Green: an empirical analysis of sustainable design approaches in fifty case studies of contemporary architecture

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**Abstract:** It is largely recognized that the world is facing fast changes in the environmental conditions, in the economic structure, and in the social dynamics. In this context, the fields of architecture and urban design have been evolving and reacting, by: addressing issues; proposing innovative design and technological solutions; and envisioning potential sustainable scenarios in a structured manner. Yet the debate around the value and the identity of the sustainability aesthetic is still open (Hosey 2012). Despite the complexity of this theoretical debate, the aesthetic of architecture and urban design has, in practice, already started to shift under the influence of economic, environmental and social sustainability principles. With the aim of shedding light on these changing dynamics, this paper proposes an empirical analysis to compare and contrast the aesthetic approaches of fifty case studies of recent buildings, which have been awarded with International sustainability prizes and/or with high score certifications by the major energy rating systems across countries. Specifically, the analysis will offer an interpretation of the relation between economic, social and environmental principles and the design solutions that were triggered by those concepts. The results of this analysis will show a remarkable variety of successful design strategies, as well as a number of design opportunities that yet need to be explored. The importance of this work is: to produce a set of statistic data that can contribute both to practice and to the theoretical debate on the aesthetic of sustainability, by providing examples of cause-effect relations between sustainability concepts and design solutions; as well as to understand and assist the changing dynamics of our built environment.

**Keywords:** Sustainable design, architecture, aesthetic of sustainability, design organization, sustainable architecture

### Introduction

It is since the Brundtland Report (1987), when the concept of sustainable development was formally defined that the practice of architecture has started evolving and searching for new means, methods, and aesthetic approaches. Aesthetic is defined here as a set of principles governing the idea of sustainability, which finds its expression in visible features of architectural form. It was not many years later that Guy and Farmer (2001) had already identified at least six approaches to sustainability in architecture, namely eco-technic, eco-centric, eco-aesthetic, eco-cultural, eco-medical, and eco-social, gauging the complexity of interpretation of the concept of sustainability in architecture. These approaches encompassed different technological solutions, sources of environmental knowledge, and images of space, which contributed to define the overall aesthetic approaches that each of those represented. Yet, ten years later Lee (2011), by editing the book: '*Aesthetic of Sustainable Architecture*', collated the contribution of at least twenty five academics and architects, in which various approaches to the aesthetic of sustainability were defined and

explained, underlining the fact that the debate on the aesthetic of architecture was still open, and more complex than before. Moreover, Hosey (2012) stretched those concepts both, by shedding light on the degree of controversy that exist in the debate around sustainable aesthetic in architecture, and by proposing a 'manifesto' of principles for a new conception of what he defines 'the shape of green'. Recently, the debate seemed to be more open than ever: the aesthetic and management matters related to sustainability are still subjected to enquiry and exploration, both in practice and in the scientific community (Helsen and Nilsson, 2016). Despite controversies and variety of approaches, aesthetic plays a crucial role in communicating the value of sustainability, and therefore maintains its important for the work of many designers and architects. Most of the work carried out in practice focuses on the changing of work organization, as well as on the architectural form. Yet, many examples of so called 'sustainable' buildings recently built, have demonstrated that projects offer far more opportunities in communicating the value of sustainability as well as in their project organizations and delivery process. This would occur by shifting the aesthetic paradigm from the architectural form to a wider range of design opportunities also concerning the building development life cycle as an occasion to communicate the value of sustainability, relying on more inclusive processes.

### **An enquiry on the current state of art: a methodological approach**

By empirically analysing the current state of practice, this work wants to present and analyse fifty sustainable projects by conceiving projects as complex systems, focusing on both architectural form and components, and delivery process. By widening the scope of the analysis in considering the delivery process as an opportunity for aesthetic design decisions, the work will attempt demonstrating that the debate on the approach to sustainability in architecture practice is still a remarkable source of innovation opportunity and development occasions. This approach will allow to shed light on the relation between sustainable design decisions, development process and environmental, economic and social effects generated; rather than attempting to define guidelines for a unified formal aesthetic definition of sustainability. In order to do so, the methodological approach utilized in this work is: 1) to select fifty case studies of contemporary buildings – located in different geographic and socio-technical contexts (i.e. Africa, Europe, USA, Asia)- among the ones that in the last ten years have received either a high score by the major energy rating system in use, or more in general sustainability and/or architectural awards; 2) to carry out an analysis of the relation between specific design decisions, development process, and sustainable effects generated; and 3) to identify tendencies, dynamics, and rationales behind each approach identified. This is an attempt to understand firstly: differences in design approaches to the concept of sustainability according to socio-technical and geographic context, and secondly: the relation between design characteristics and social, environmental, and economic effects, as well as the impact of design decisions and project delivery process.

### **A possible analytical method**

The analytical method utilized relied to analyze the case studies on the conception of building seen both as product and processes (Turin 1980). To do so, the building components analyzed for each case study selected are selected on the basis of the EU building directive 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 19 May 2010, which - among other aspects - defines the projects aspects which are sensitive to sustainability. These components are dimensions, shape, floor number, access and circulation, structure,

environmental control systems, water treatment. The process is explored in accordance to the principle of building/project management identified keys aspects of project productions. Specifically, the analytical areas analyzed for each areas are: commissioning, financing methods, building programing, form and shape, technical specifications, contract relations, project production, project erection, work coordination, drawing organization, project use and maintenance.

Each building component and process characteristic of the case studies selected are assessed according to a number of parameters defined to explore environmental, social and economic effects. The type of effects - as highlighted in table 1 - are: *mixité*, social inclusion, wealth, education, safety for the social discipline; market expansion, competitive advantage, comparative advantage, knowledge acquisition, property/land value increase for the economic discipline; and emission reduction, resource generation, waste reduction, environmental sustainable strategy introduction, technological performance increase for the environmental discipline. These effects are assessed on a scale from one to five, in terms both type if impacts/change and results. The impact or change is analysed by relying on a scale of degree of change from the standard practice - irrelevant change - to total novelty - radical change (Henderson and Clark 1990).

Table 1. The table below shows the assessment parameters utilised in the proposed assessment method

EFFECTS	TYPE OF CHANGE	SCALE OF EFFECTS	TYPE OF EFFECTS
Social Effects	Irrelevant, Modular, Incremental, Architectural, Radical	1 to 5	<i>Mixité</i> , social inclusion, health, wealth, education, safety, et cetera
Economic Effects	Irrelevant, Modular, Incremental, Architectural, Radical	1 to 5	Market expansion, competitive advantage, comparative advantage, knowledge acquisition (patents), property/land value increase
Environmental Effects	Irrelevant, Modular, Incremental, Architectural, Radical	1 to 5	Emission reduction, resources generation, waste reduction, sustainability strategy introduction, technological performance increase

The output of the analysis provided a mapped set of information regarding the degree of sustainable innovation, the type of approach of sustainability and the social, environmental and economic effects that the design decisions and the process organization produced. As it is showed in figure 1 and 2, it was possible to produce a graphic output from the analysis which demonstrate firstly, the distribution of sustainability type decisions made on the case study analysed (figure 1); and secondly the relation between building components, process characteristics and sustainability effects achieved (figure 2). This analysis was then conducted on each of the fifty case study selected.

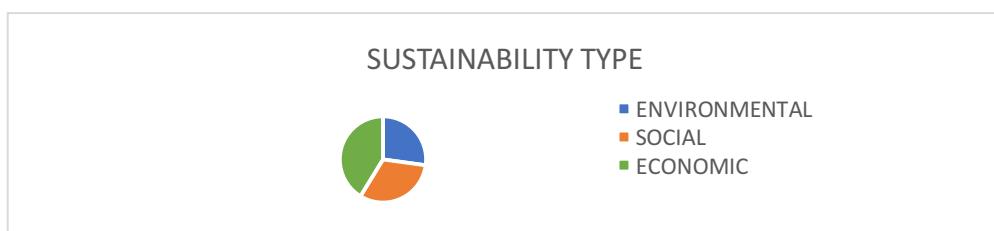


Figure 1. The figure shows and example of the distribution of sustainability type design decisions for one of the case study analysed

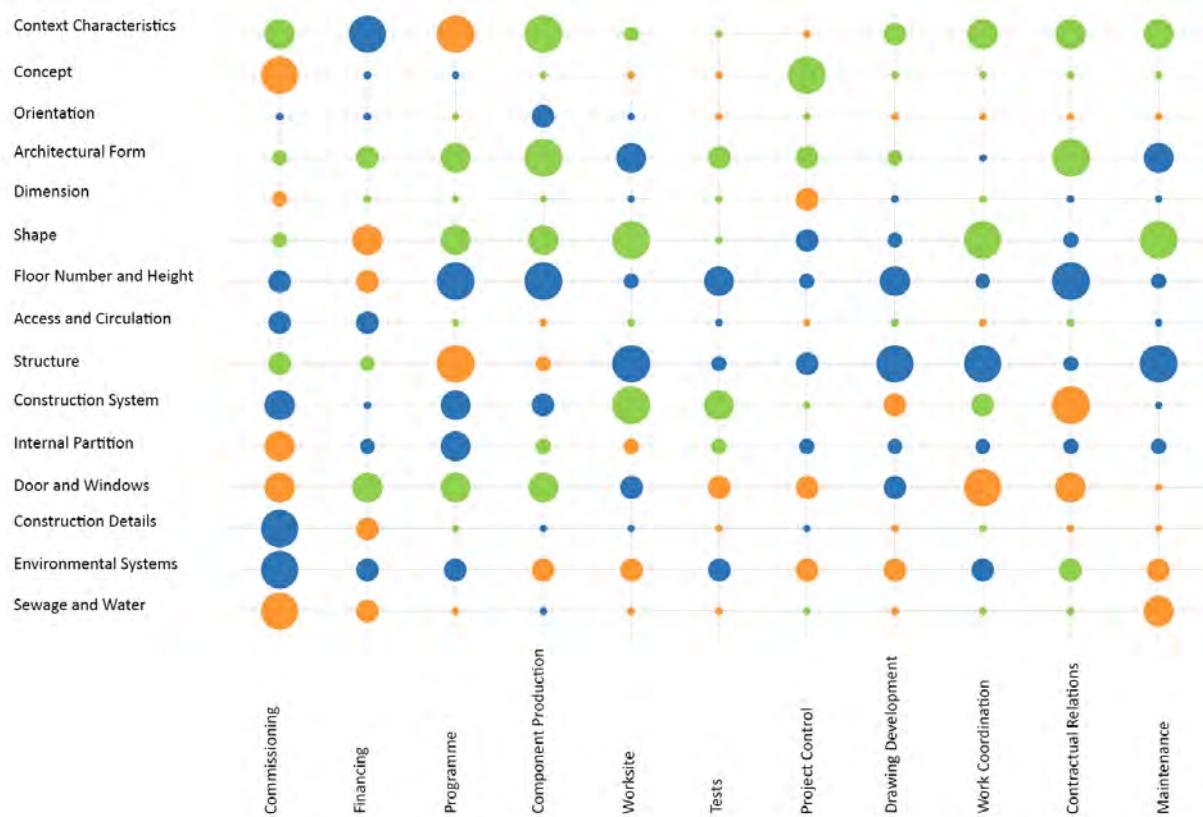


Figure 2. The figure shows the relation between building components, process characteristics and type of sustainability effects and impact produced during the delivery design and delivery process in one of the case study analysed. Each colour identifies the type of sustainability (environmental, social and economic) and the ball dimension identifies the degree of impact that the design decision had on the delivery process

### The results: The aesthetic approach of fifty case studies

The result of the analysis showed great variety of approaches to the sustainability matter among the analysed case studies. The differences are concerned with both the aesthetic – as a set of definitive characteristics – as well as with the effects produced by each project in terms of environmental, economic, and social outcome.

At a first glance, at least three major approaches to the sustainability needs were detected. These approaches followed either the environmental, economic or social declination of the concept of sustainability, showing aesthetic characteristics that were a reflection of one of these approaches. Rarely, an equilibrium was found between the three dimensions of sustainability in the same project. These distinctions largely influenced the aesthetic characteristics in which the value of sustainability was placed. It was possible therefore to identify building elements and/or design decisions which were more relevant in the production of either an environmental, economic, and/or social effect or result.

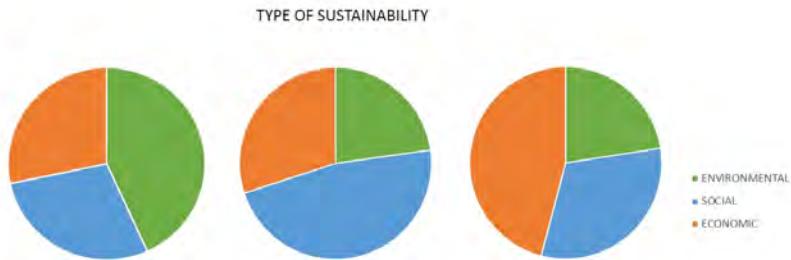


Figure 3. The figure shows the type of sustainability distribution in the case study analysed

Most of the case studies that showed a higher attention to the social sustainability were able to do so because of their scope, location, and process of production. Most of those projects were located in a developing country, with extreme climate conditions, low industry skills and technical development, and strong social contracts. Aesthetic components which characterised the opportunity for sustainability design decisions were: use of local materials, opening design, roof systems type and shape, orientation, access, ease of construction, and building procurement method. Mostly though, the critical factor to achieve social sustainability was the participation and the social inclusion during the production and erection process of the buildings, which served not only to define a common identity, but also to train labour with new skills, and to produce the larger impact socially within the community. The aesthetic of the sustainable choices in these category of projects was the reflection of the participation and the ownership of the building by the community, not only by relying on the physical participation in the construction process, but also in the ability to rely to sets of physical building features that represents well known elements in the local areas and therefore representing a cultural ownership by the local population, i.e. local materials, traditional layouts, use of natural ventilation by utilizing double roof ventilated type as a reflection of the climatic conditions, et cetera.



Figure 4. The images show an example of mapping of social sustainable type of project: The Gando Primary School by Francis Kéré, In Burkina Faso, Africa (Photo: <http://www.kere-architecture.com/projects/primary-school-gando/>)

The case studies that were more environmentally oriented were largely characterized by ownership type, government incentives, capital availability, technological robustness and availability. The attention toward the environmental issue was in those cases actualized by relying, where possible, on the use of both technologies and/or natural solutions, particularly concerning with lighting and ventilation. This latter was though the aspect that was most

relevant in the overall design organization of the projects analysed. Moreover, the presence of green roofs, green walls, complex engineering solutions, as well as the generation of new microclimates, energy consumption reduction or energy production were also the aspects that the environmental approach mostly followed, in accordance with the analytical parameters of the major energy assessment methods currently utilized in practice (i.e. LEED, BREAM, et cetera). Those projects reflected aesthetically the scientific effort of technologically solve the energy consumption issue, and therefore relied on displaying the feature which were aimed at covering this function.



Figure 5. The images show an example of mapping of an environmental sustainable type of project: The Academy of Science by Renzo Piano in San Francisco, California, USA (Photo: <http://www.archdaily.com/6810/california-academy-of-sciences-renzo-piano>)

The case studies that were more oriented toward an economic sustainability type did not necessarily found a geographic match in their location, but rather were strictly related to the capital availability of economic condition of the end-user and/or the client. The economic sustainability in these cases was found in the re-use of materials, use of rough finishes, use of rational geometrical shapes and layouts, use of standard construction systems, ease of construction, participation of the industrial community in supplying products and materials, type of financing (i.e. crowd funding, donations, volunteering, et cetera), and procurement type. The aesthetic of these projects was generally the expression of a set of functional needs, which was the main visible feature of the projects.

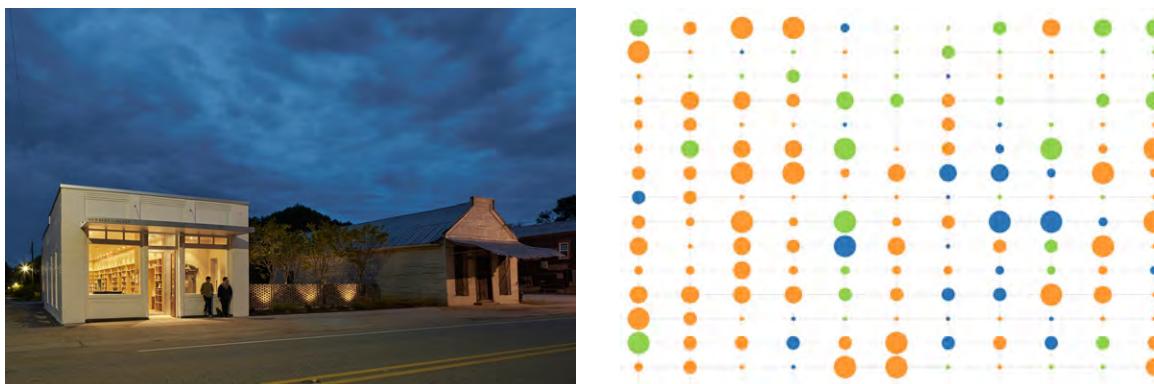


Figure 6. The images show an example of mapping of an economic sustainable type of project: The Newbern Library in Newbern, Alabama, USA by Rural Studio (Photo: <http://newbernlibrary.ruralstudiodblogs.org/>)

Although most of the projects analysed tried to express their sustainability approaches in a set of visible features (aesthetic choices), either in the type of materials, use of construction systems and finishes, or shapes and layouts, some remarkable results were represented through those projects, which did not attempt to use architectural set of elements to represent a sustainable approach, rather they tried to rely on the ‘aesthetic of the effects’ that sustainable design choices produced to communicate their own value.

One example of these externalities was the case study of the office building ‘The Edge’ by PLP Architecture in Amsterdam, which showed a strategy that empowered the users of the building to monitor the environmental effects of the building by highlighting all the building components that were directly dependent upon the interface with the users’ behaviour. To this end, a number of ‘green plugs’ were located all over the building to encourage users to use electricity produced by alternative sources, as well as the company Philips developed an ad-hoc phone application for the building users to take part into the energy management and consumption of the building. In this case, by showing the aesthetic of the ‘sustainability effects’, rather than the architectural components characteristics, the project offered an example of new feature of the building functioning that could be a new design opportunity, such as the interface with the building users.

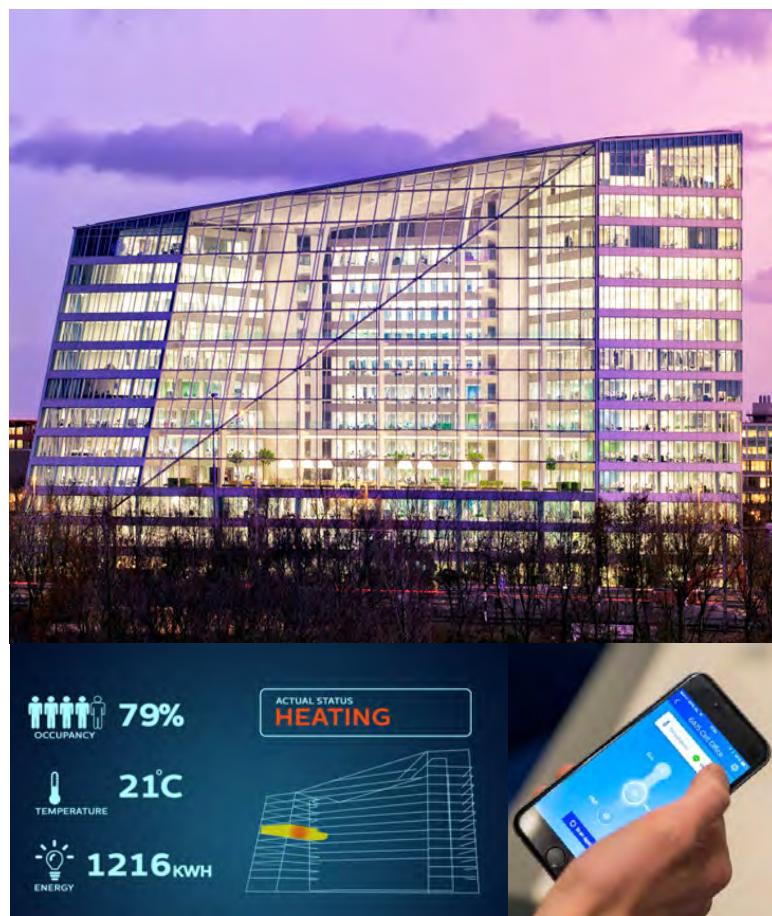


Figure 7. The images show the building ‘The Edge’ in Amsterdam and an example of the app developed by Philips for the interface between users and building management (Photo: <http://www.usa.lighting.philips.com/cases/cases/office/edge>)

## **Discussion: The influence of the social economic and environmental context on the design solutions and the new opportunities detected**

At a first glance, the results produced by the analysis conducted were in line with the six type of sustainability approaches already discussed by Guy and Farmer (2001), and later expanded by Lee (2011). Yet, by widening the scope of the analysis to both the artefacts and the delivery process, this work was able to expand the reflections that Hosey (2012) conducted on the aesthetic role of sustainability. Specifically, this work pointed out the importance to understand the value and the opportunity that the delivery process can offer in communicating the importance of sustainable choices by design. By understanding these opportunity, the aesthetic role that has been generally covered by the architectural form, can also be refined and amplified by new design areas concerned both with architectural features and delivery process (for instance: the interface with the users for example, the construction process, or the industrial participation of the designers in a tight collaboration with the suppliers or manufacturer, et cetera). Being sustainability a complex matter, its aesthetic - conceived it as a set of features governing the idea of sustainability - can be find not only in the architectural form but also in the life of building artefacts from its conception, delivery and life cycle, in order to fully expressing the value and the importance of making sustainable design choices.

## **Conclusions**

In a context of fast changes in the environmental conditions, in the economic structure, and in the social dynamics, a fast response by architects and designers is crucial to address issues; propose innovative design and technological solutions; and envision potential sustainable scenarios in a structured manner (Grosso, et al, 2015). To do so, cultivating and mastering the aesthetic component of the design decisions is an essential practice to ensure the effective communication of value and meanings of sustainability. The importance of doing so relies in the ability of the architectural and design field to take actively part into the societal discourse on sustainable development and to propose solutions that can positively encompass the complexity of sustainability development. It is critical therefore that conceiving aesthetic as a tool for effective communication of sustainability principles becomes a structured practice, which encompasses a wide range of aspects from the architectural form to the artefacts delivery process and life cycle, as a reflection of the changes that our societies are currently facing.

## **References**

- Guy, S., Farmer, G. (2001). Reinterpreting Sustainable Architecture: The Place of Technology. *The Journal of Architectural Education*, 54(3), pp. 140-148)
- Hensel, M., Nilsson, F., (2016). *The Changing Shape of Practice*. London and New York: Routledge, Taylor and Francis Group
- Hosey, L., (2012). *The Shape of Green, Aesthetic, Ecology and Design*. Washington| Covelo| London: Island Press
- Lee, S. (2011). Aesthetic of Sustainable Architecture. Rotterdam: 010 Publisher
- Turin, D. (1980). What do we mean by Buildings?. *Habitat International*, 5, pp.271 -286
- Grosso, M., Chiesa, G., Nigra, M. (2015). Architectural and Environmental Compositional Aspects for Technological Innovation in the Built Environment. In: *Heritage and Technology. Mind Knowledge Experience*, La Scuola di Pitagora XIII International Forum Le vie dei Mercanti, Capri 11-13 Giugno 2015



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Formal Representations of Seasonal Adaptation - On a Search for Sustainable Architectural Forms

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**Abstract:** Since sustainability emerged as the most important keyword for the last decade, the question whether it has any formal representation has been at the centre of architectural debates. At the core of debates, the reconsideration of the relation between climate and architectural form is based on the recognition that the main principles of sustainability are rooted in the environmental conditions of the building site, including its climate. In regions with hot-humid summer and cold-dry winter, however, the seasonal differences require different considerations for the same building depending on season. This is the reason why the concept of seasonal adaptation is at the focus of interest in sustainable architectural design. Different examples of seasonally adaptive buildings are analysed here to make clear the relation between their concept and the architectural form. Through the analyses, it is assumed that the concept of seasonal adaptation might not have any concrete form, but it has the abstract image of form as periodically changing entity. Based on this finding, the aesthetics of seasonal adaptation can be referred as the aesthetics of periodical change represented in a 'fluctuating form'.

**Keywords:** sustainability, seasonal adaptation, aesthetic, architectural form, fluctuating form

### Introduction

In our environment-conscious era, energy efficiency emerged as one of the most important requirements toward buildings. However, it often confronts other human needs, like indoor comfort, health or aesthetic needs. In vernacular architecture, indoor comfort and health were maintained through the appropriate orientation, form, proportion, spatial layout or building materials. Beyond merely satisfying aesthetic needs, architectural form has served indoor comfort and health. But with the development of technology, traditional methods were replaced by efficient building equipment, making architectural form free from the environmental circumstances. The freedom of expression encouraged architects' freakish intellectualism, and leaded to the degradation of the aesthetic quality of the built environment. On the other hand, active methods were soon proved to be immensely energy-consuming, necessitating new sustainable design strategies. As such strategies would in turn require the reconsideration of passive methods, they are commonly expected to result in a new aesthetics through re-relating architectural form to indoor comfort and health issues.

Sustainability is already the most important keyword in almost every aspect of Life. In architecture, based on the recognition that the main principles of sustainability are rooted in the environmental conditions of the building site, including its climate, there is a renewed interest for climate responsive design. In regions with dry-cold winter and hot-humid summer, however, seasonal difference requires different considerations for energy efficiency, health and indoor comfort of the same building depending on season. Passive methods encourage

natural ventilation, which provides comfortable condition for summer, but such traditional buildings are cold in winter. To provide comfortable conditions for winter, either immensely energy-consuming equipment is used or buildings are made to be super-insulated and airtight, which often causes health problems for the occupants. To solve the equation with the three variables (energy efficiency, health, comfort), the idea of seasonal adaptation was invented. It is based on the analogy of ‘adaptation’ in Nature. That is to say, seasonally adaptive building can adapt to seasons through an environmental change response mechanism, just like a living organism, thus it has the optimal parameters to maintain healthy and comfortable indoor conditions with low energy consumption throughout the year. On an attempt to getting closer to the understanding of the aesthetics of sustainable architecture, this paper examines the relation between the concept of seasonal adaptation and the architectural form.

## **Architectural Form and Aesthetics**

### ***The evaluation of Architectural Form***

It is widely accepted view that form is the biggest factor to contribute to the aesthetic quality of a building. The evaluation of form is, however, a very complex issue. Without going to details of cognitive psychology, one can assume that people basically evaluate form through a three-stage process of perception-cognition-evaluation. In the stage of perception, the physical stimulation of the sense organ – light falling on the retina – arouses neural impulses. In the stage of cognition, signals sent to the brain by the nervous system are identified and interpreted. Cognitive mechanism is pre-conscious: people understand what they perceived depending on their memory, expectation and attention (Goldstein, 2009). Finally, people judge about what they understood according to their value standard.

There are different theories about how people evaluate visually perceived matters. According to some theories, people tend to positively evaluate something familiar to them, because familiarity with a thing gives them a sense of security. Zajonc asserted that repeated exposure to a thing enhances the observer's positive attitude towards it, by unconsciously making the thing visually familiar to him/her (Zajonc, 1968). The relation between the mere exposure effect and aesthetic preference has been stated also in art theories. According to Cutting, “(a)rtistic canons are promoted and maintained by a diffuse but continual broadcast of images to the public by museums, authors and publishers. (...) Tacitly and incrementally over time, it teaches the public to like the images, to prefer them, (...) and to want to see them again” (Cutting, 2007). It is essentially the same with our built environment. To buildings, which we have been exposed to us for long, we tend to attach positive feelings, while we are often resistant toward new architecture at the first sight (Tange, 2011). By the same logic, as each era has its commonly favoured architectural form reflected in the built environment, it is reasonable to assume that people from the same era share a kind of common aesthetic sense. The next section is a follow up of it throughout a brief history of architecture.

### ***The Transformation of Aesthetics over Time***

Architectural aesthetic differs depending on era. When talking about the aesthetic of pre-modern architecture, we have to think in terms of the shape of details embodied in the ornament rather than the overall building form. Historical styles had their favoured motives that very often took the shapes of natural world in that climate. As Nature used to be the most common source of sensory input before the industrial revolution, it provided a familiar set of formal vocabulary for people. At the same time, geometrical ornament is primordial

among decorative elements. By the growth of culture and knowledge, a set of geometrical artistic forms has gradually developed based on the form of cultural artefacts (Meyer, 1957). Up to Art Nouveau, ornament – either organic or geometric – has been at the centre of aesthetic debates. Then the first notable shift came with the Modern movement: from the aesthetic of decorative details to the aesthetic of the overall building. In the machine age, ornament was eliminated and emphasis was put on the function of the building that most often had a simple geometric form. Due to the development of science and technology, the new aesthetic of the “white cube” – the symbol of Modern architecture – has spread independently from climate or culture, to deserve the name “International Style”. For decades, architects have been working on the subconscious promotion of its canon through the continuous broadcast of the “white cube”-image to the public all over the world.

As everyday life became more and more complex, the subject of aesthetic gradually shifted from simple forms to complex forms. In order to study how to attain meaningful perceptions in the chaotic world, Gestalt psychology was re-employed in architectural and urban theories. In Gestalt, form was considered not as a simple assemblage of parts but as an “organization of patterns and objects” based on specific laws, which architects of the era were eager to apply for the built environment. Arnheim explored the perceptual consequences of order and disorder in architecture (Arnheim, 1954). Lynch applied Arnheim’s ideas to urban design, and examined the possibilities to make the city “imageable” through proposing a set of complex relations among its elements (Lynch, 1960). Meanwhile, urbanization involved the concept of ‘mobility’, and the aesthetics of complexity has transformed into the aesthetics of change. As a result of economic development, sudden population overgrowth resulted in an uncontrollable urban sprawl in big cities. To keep pace with the continuous growth of cities, architects had to think in terms of enlargement and to invent the concept of ‘growing forms’. To foster the image of ‘growing form’, analogy from Nature was borrowed again. The new analogy was, however, entirely different from the pure imitation of natural shapes. It evoked the image of nature in a more abstract way: through referring to the process of growth of living organisms. The next big shift in architectural aesthetic is obviously approaching. But how will the aesthetic of an environment-conscious era look like? Does sustainability have its own aesthetics at all? To help the answers, this paper examines what kind of representations seasonal adaptation have, and how it fits in the history of the aesthetics of architectural form.

### **Analysis of the Examples of Seasonal Adaptation**

Built examples, general ideas and unbuilt prototypes are analysed here in terms of the relation between the concept and the architectural form. Projects are categorized according to the different analogies of seasonal adaptation in nature. Type1 contains projects that refer to the general idea of ‘changing dwelling according to season’. Type2 contains projects that are based on the concept of ‘flexible building layout’ to provide optimum condition for every season. Type3 contains projects, which relate to the idea of ‘smart building envelopes’ in some ways. Since this idea covers a wide range of related concepts however, Type3 is subdivided into a) Removable Building Skin, b) Double Skin, c) Self-orienting Solar Roof, d) Mechanical Brise Soleil and e) Smart Materials. ‘Removable building skin’ includes projects that respond to seasonal change through casting off the building envelope. ‘Double skin’ includes projects that respond to seasonal change through switching the ‘behaviour’ of the building envelope. ‘Self-orienting solar roof’ and ‘mechanical brise soleil’ includes projects that respond to seasonal change due to the movement of some parts of the building envelope

depending on the location of the Sun. ‘Smart materials’ includes projects that respond to seasonal change through the change of the physical features of the building envelope.

### Type1 – Changing Dwelling According to Season

Changing dwelling according to seasons is not a new idea. In Japan, already in the Kofun period (A.D. 3rd Century–538) the pit house for winter coexisted with the raised-floor house that was used from spring to autumn. Although the idea itself could have hypothetically infinite formal representations, building form was constrained by the level of technical development of that period. The circular or rectangular thatched roof of the pit house was constructed above an underground hole. It was supported by a wooden log frame covered with soil (Fig.1). Soil, as a seasonal heat storage, stored the summer-heat and kept the house warm in winter. On the contrary, the raised-floor house most often had rectangular thatched roof supported by vertical wooden walls from the elevated floor. Its floor was laid some ten centimetres above the ground across horizontal wooden beams, which were supported by small wooden columns (Fig.2). The raised-floor promoted air circulation below the house, and it therefore had moisture protection and cooling effect in the hot and humid summer.

### Type2 – Flexible Building Layout

The embryo of the concept of ‘flexible building layout’ has already existed for long. Strategies like changing bedroom, limiting bedroom only to sleeping or rearranging the room layout seasonally have often been used for making the living environment comfortable in the hot-summer/cold-winter zone. As the improved interpretations of the original idea, there are recent projects where the location of rooms, their interrelations, or the orientation of some rooms can change depending on season. E.g., *Dynamic House* by D\*House (London studio) is a bold proposal to fold a building into several configurations, based on the logic puzzle of H. E. Dudeney. Four distinct shapes correspond to four parts of the house: a living room, a bath room and two bedrooms. The four parts can have eight configurations with different layouts. Depending on the layout, internal walls become façades and external walls become internal ones outside windows become inside doors and vice versa. In winter, the building has the most compact form to minimize heat loss. From winter it gradually unfolds, and have the biggest surface in summer. From summer to winter, the building gradually transforms back again (Fig.3). *Dynamic House* has some limitations in terms of shape because of the most compact shape constraints of the specific mathematical puzzle. However, the concept itself to fold a building into different configuration does not restrict the architectural form.



Figure 1. Pit House.

Source:<https://traveldreamscapes.wordpress.com/2013/09/09/japan-chikuma-city-mori-shogunzuka-kofun/>

Figure 2. Raised-floor House.

Source:<http://factsanddetails.com/japan/cat16/sub105/entry-5293.html/>



Figure 3. *Dynamic House* by D\*Haus.

Source:  
<https://www.dezeen.com/2012/11/06/shape-shifting-house-by-the-dhaus-company/>

### Type3 – Smart Building Envelope

Among sustainable architecture issues, smart building envelope that can adjust to changing conditions has been receiving special attention. Most common examples include Climate Adaptive Building Shell (CABS), which “has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance” (Loonen, 2013). CABS has many different types. Among them, proposals related in some or other ways to seasonal change are taken here.

#### Removable Building Skin

The idea to adjust to seasonal change through casting off the building skin or a part of it one among CABS ideas. By using very simple technical devices, buildings can ‘moult’ to have cooler conditions for the summer and wear an additional ‘coat’ to have warm condition for the winter. This simple analogy is used in *Sliding House* by dRMM (London studio) among others. *Sliding House* consists of a garage, a guest annex, the main house with a roof terrace bathroom and the attached glass living room, as well as the sliding house (skin) itself (Fig.4). Except the garage that stands independently, other parts of the composition are connected through some rail tracks. In summer, which is not too hot in that area, the skin of the building can be removed to let the glass living room to collect sunshine and the bathroom to have a nice view. The sliding skin is an autonomous structure, which incorporates a thick insulation. By moving the skin into the position to cover the living room, the inside can be kept warm in winter. Movement is ensured by electric motors incorporated in the thick walls. Buildings of the composition have conventional forms defined by the simple pitched roofs. Because of the overlaps of different buildings depending on time, the size and the shape of the buildings are necessarily adjusted to each other. However, the concept itself does not restrict the architectural form: similar effect can be expected through any kind of building shape.

#### Double Skin

“A double skin façade can be defined as a traditional single façade doubled inside or outside by a second, essentially glazed façade. Each of these two façades is commonly called a skin. A ventilated cavity - having a width which can range from several centimetres to several metres - is located between these two skins” (Loncour, 2005). By mechanically controlling the movement of air in the cavity, the building can adjust to different climatic conditions. *One Angel Square* by 3Reid and Waagner Biro is a classic example of it. In, summer fresh air enters the cavity between the two skins from below. As it is warmed up by the Sun through

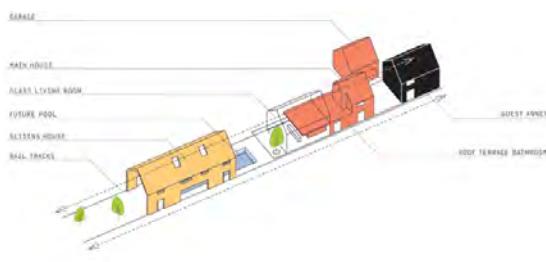


Figure 4. *Sliding House* by dRMM.

Source:

<https://www.dezeen.com/2009/01/19/sliding-house-by-drmm-2/>



Figure 5. *One Angel Square* by 3Reid and Waagner Biro.

Source: <http://www.archdaily.com/337430/1-angel-square-3d-reid>

the glass skin, it raises. Hot air leaves from between the double skin at the top of the façade. This way of soaking up air passively reduces cooling costs. In winter, the upper side of the cavity closes automatically, and the air layer – stuck between the double skins and warmed up by the Sun – works as insulation, reducing heating costs. The shape of the overall building is often compared to a sliced egg centred around a diagonal slice, the central atrium topped by a glass roof (Fig.5). But it does not directly refer to the concept of the double skin itself, which could allow hypothetically infinitive kind of formal representations.

### *Self-orienting Solar Roof*

Self-orienting solar roof is a roof with solar panels, which can self-adjust its angle to the position of the Sun in order to acquire maximum amount of solar energy by minimum effort anytime. *Casas Em Movimento Solar Homes* by the University of Porto is one of the representatives of this ideas. It is a simple box dwelling enclosed by a metal truss system covered in photovoltaic panels from three sides (Fig.6). The basic idea is the combination of because of the mechanical system integrated in two kinds of movements: the rotation of the with solar panels. The building can rotate up to 180 degrees overall building and the pivoting of the truss the truss. The movement of the house is set to track the sun automatically. At the same time, the truss-roof is able to pivot by up to 60 degrees for even better solar exposure. The shape of the building is basically not related to the idea of two-dimensional movement, but the truss should adjust to the geometry of the building by technical reason, and the surface of the roof is better kept flat for good energy performance.

### *Mechanical Brise Soleil*

The original idea of Brise Soleil is to reduce heat gain by shading of large glass façades. Through mechanizing the idea, however, Brise Soleil can already adjust also to seasonal difference: the incorporated intelligent equipment can detect the exact position of the Sun all through the year. *Al Bahar Towers* by Aedas Architects is the modern version of the *Arab World Institute* in Paris by Jean Nouvel's. Due to the extremely hot weather, proper shading for the high glass tower was a big challenge. A traditional Islamic lattice shading device – the *mashrabiya* – was used as model. The geometries of the façade panels were designed based on the calculated Sun exposure and angles of the specific day and time. The skin with the façade panels works as a curtain wall supported in front of the glass wall by an independent frame. Panels respond to the movement of the Sun, and close when it has the most critical angle. They are composed of triangular-shaped components, and when they open, their



Figure 6. *Casas Em Movimento Solar Homes*. Source:  
<http://www.portilame.com/en/1-synergies/5-casas-em-movimento/>



Figure 7. *Al Bahar Towers*.  
Source:  
<https://jp.pinterest.com/pin/85920305369409129/>

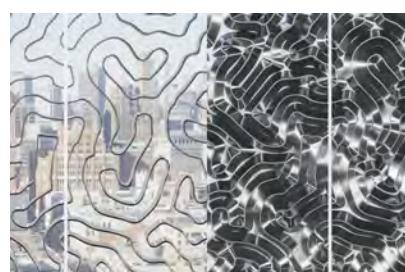


Figure 8. *Homeostatic Façade System*. Source:  
<http://internationalfacade.com/news/general/homeostatic-building-facade/>

composition is similar to several of opening morning glory flowers (Fig.7). Purely in terms of shading, however, several other shapes would work as well. In turn, the formal geometry of the towers was designed to complement the shading effect. The cylindrical shape was decided as the most efficient one in terms of wall-to-floor area that also ensures the largest volume with the least surface area. It can therefore be said that although the overall shape is not a direct derivative of the original concept of shading, it is partially influenced by it.

### *Smart Materials*

In general, smart material can react to the changes of their environment on their own, through a change in their volume, colour or viscosity, etc. Smart building materials are various, but it is beyond the scope of paper to discuss all in detail. Here an unbuilt prototype, which can react for seasonal change of the temperature and light conditions is taken. Homeostatic Façade System by Decker Yeadon architects is a muscular structural façade, which can reduce solar gain by changing the configuration of the structure of its material. The façade consists of a mess of silver-colour squiggles that open and close in response to temperature change to regulate interior temperature. The material used in the façade is an electroactive polymer that transforms electric energy into mechanical work to change shape. When it is hot, electricity deforms the squiggles that expand, and when it is cold, squiggles are contracted (Fig.8). As a result, façade pattern changes, but it does not influence the overall building form.

### **Conclusion**

Based on the analyses, it was found that the idea of seasonal adaptation does basically not limit the architectural form, at least not in a direct way. Only in an indirect manner, Type3 was found to incorporate certain constraints that were somewhat related to the original idea. In case of a) Removable Building Skin, the forms of the parts were slightly restrained, but only in relation to each other to make it possible for the different parts to be overlapped. In case of c) Self-orienting Solar Roof, keeping the roof panel flat for better performance seems reasonable, but these constraints have little influence on the overall shape. In case of d) Mechanical Brise Soleil, although the overall shape of the building is partially influenced by the aim of shading, it is not really the direct derivative of the concept of mechanical brise soleil. At the same time, the representation of the concept of seasonal adaptation was revealed in the change of the form and/or function according to seasons in all the projects. In Type1, Type2, as well as a) Removable Building Skin and c) Self-orienting Solar Roof of Type3, the overall form or a large part of it changes according to seasons. In d) Mechanical Brise Soleil, the form of small building parts, and in e) Smart Materials the texture of the building envelope changes. But in case of b) Double Skin, the representation of seasonal adaptation is limited only to the functioning of the building envelope, and is basically not recognizable on the architectural form. One can thus assume that – except the case of b) Double Skin – the common characteristic of the projects can be seen in the concept of periodical change of form. Moreover, seen in the history of architectural aesthetics, the aesthetics of seasonal adaptation can be understood as the next link in the chain of (i) the aesthetics of details (shape), (ii) the aesthetics of the whole (simple form), (iii) the aesthetics of complexity (complex form) and the (iv) aesthetics of gradual change (growing form). Although its form-image is also dynamic, it is different from the gradually changing (growing) image of form that was invented to adjust to the growing population. It is a kind of fluctuating form, changing periodically according to seasons. The aesthetics of seasonal adaptation can therefore be referred as (v) the aesthetics of periodical change (fluctuating form).

All in all, one can say that the concept of seasonal adaptation might not have any concrete form, but it has the abstract image of form as periodically changing entity. Although this conclusion is limited to the concept of seasonal adaptation, by the similar logic it can be assumed that sustainability – which is an even vaguer concept – nor can have any concrete formal representation. However, judging from the tendency of architectural education, an aesthetic canon of sustainability will probably be fostered and handled unconsciously to the public through continuously exposing them to some familiar set of images from Nature.

## References

- Arheim, R. (1954). *Art and Visual Perception: A Psychology of the Creative Eye*, University of California Press.
- Cutting, J. E. (2007). "The Mere Exposure Effect and Aesthetic Preference", In: P. Locher et al. (eds.) *New Directions in Aesthetics, Creativity and the Psychology of Art*. New York: Baywood, pp. 33-46.
- Goldstein, E. (2009). *Sensation and Perception*. 8<sup>th</sup> Edition. Wadsworth: Cengage Learning, pp. 5–7.
- Loncour, X., et al. (2005). Ventilated Double Skin Façades: Classification & illustration of facade concepts. *AIVC Contributed Report 3*, 49 pp.
- Loonen, R. C. G. M., et.al. (2013). "Climate adaptive building shells: State-of-the-art and future challenges", *Renewable and Sustainable Energy Reviews*, 25, pp.483-493.
- Lynch, K. (1960). *The Image of the City*. Cambridge: The MIT Press.
- Meyer, F. S. (1957). *A Handbook of Ornament*. New York: Dover Publications, Inc.
- Tange, K. (2011). *Ningen to Kenchiku: Dezain Oboegaki*. Tokyo: Shokokusha, pp.167-169.
- Zajonc, R. B. (1968). "Attitudinal effects of mere exposure", *Journal of Personality and Social Psychology*, 9 (2, Pt.2), pp.1–27.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Design of Low-energy Homes using Thermal and Daylight Simulations in Interactive Generative Parametric Modelling

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**Abstract:** There is an increasing effort to integrate building simulation tools into architectural CAD tool environments to enable evaluation of the effect of architectural considerations on other building performance issues such as energy use, thermal indoor climate, and daylight conditions, during the early design stages. One approach is to generate design advice using the concept of *generative parametric modelling* (GPM). GPM approaches often make use of an optimisation algorithm to automatically generate solutions that fulfils some predefined boundary conditions set by the designer – including architectural rules. The designer can revise the generated solutions and accept or discard any solutions e.g. from an architectural perspective. GPM setups where the designer has facilities that give direct control over the GPM input and output are sometimes referred to as *interactive GPM*. This paper presents an example of how a proposed interactive GPM framework can be used for generating prescriptive information to designers of a low-energy detached single-family home in Denmark. In relation to this, it is investigated how a set of architectural rules identified from an analysis of prevailing architectural styles may affect the solution space.

**Keywords:** Building design, Architecture, Parametric modelling, Energy use, Daylight, Indoor climate.

### Introduction

There is an increasing societal pressure on the building industry to produce low-energy homes without compromising on function, aesthetics, comfort, cost, and other performance considerations. As a consequence, building designers must become increasingly aware of how potential design decisions affect the fulfilment of energy performance targets. Computer-based building energy modelling (BEM) is ideal for generating this information. Within the recent years, there has been an emerging development towards coupling BEM tools with architectural CAD tools, for example DIVA-for-Rhino (2017), Openstudio (2017) for SketchUp, Green Building Studio (2017) for Revit, and ICEbear for various CAD tools (Lauridsen and Petersen, 2014). The immediate benefit is that building designers now have access to in-model BPS-based predictions, and consequently do not need to spend time on making and updating parallel geometric models in third-party BEM tools. However, this development needs to embrace realisations from the past, namely that simulation tools used for an evaluative purpose is an inefficient use of BEM (Petersen and Svendsen, 2010). Instead, BEMs should be used more prescriptively in the design process to generate design advice; by doing so, designers may find that they save time perusing design paths doomed to fail, and instead uncover unprecedented possible design options.

There are various proposals for procedures and methodologies on how to use BEM tools for generating design advise, see e.g. overview in Petersen and Svendsen (2010) and

Østergaard et al (2016), but there is not much knowledge on whether these proposals are adopted by designers or design teams in real building design projects (Petersen et al, 2014). The notion is that it is rare, and a reason might be that current proposals for procedures and methodologies are only assumptions of, or they interpret wrong, what architects actually need (de Souza, 2011). However, there is emerging evidence that integration of BEM into architectural CAD tool environments might be a catalyst for the use of BEM-generated design advice in actual architectural design practice (Petersen et al, 2014). One approach to generate this form of design advice is the concept of *generative parametric modelling* (GPM).

### ***Generative parametric modelling in architecture***

Generative parametric modelling (GPM) in architecture is basically a concept that seeks to exploit the capabilities of computer-based modelling to automatically generate prescriptive design advice rather than using models for sheer performance evaluation in a manual trial-and-error design process. A more formal definition of the digital design framework that GPM can be considered as part of is provided by Oxman (2006). One of the earliest reported uses of BEM-based GPM – though not called GPM at that time – was the work by Radfort and Gero (1980) who used a thermal simulation tool and optimisation to generate design advice in the form of trade-off diagrams for performance-decisive parameters. Examples of more recent endeavours, e.g. Ullrich et al (2013) and Lauridsen and Petersen (2014) within thermal and daylight simulation and Watson and Wonka (2008) and Vangeas (2010) in urban planning, also couple models to optimisation algorithms to generate prescriptive design advice; however they may vary in optimisation objective, constraints, choice of optimisation approach, and presentation of results.

There seems to be a notion that the ‘raw’ script-based nature of GPM poses an inhibition threshold for many designers and visual artists which is why interactive GPM systems have been developed. Lipp et al. (2008; 2011) gave designers direct and persistent control over the generated solutions from a shape grammar approach to architecture, Merrell et al (2011) enabled the user to set up rules before GPM automatically generated suggestions for furniture arrangements in rooms, and Lauridsen and Petersen (2014) proclaimed that their proposed GPM framework “does not work without human designer to formulate the rules of an architectural idea and its boundary conditions”.

The major components in CAD-based GPM in architecture seem to be: 1) a CAD model of the geometry/shape to be investigated, 2) coupling the CAD model to an optimisation algorithm and, optionally, a performance predictor (e.g. BEM), and 3) ensuring that designers can interact with the GPM input and/or output.

### ***Aim of this paper***

This paper presents an example of how a BEM tool integrated in a CAD tool in principle could be applied for interactive GPM-based architectural design of low-energy detached single-family homes in Denmark. The example takes offset in a short analysis of the historical development of the typical Danish detached single-family home that seeks to identify a set of long lasting architectural traits – or “rules” – which also can be regarded as valid for today’s design practice. The purpose of identifying these rules is to make this study a more practice-oriented example of how GPM can be used to help designers meet low-energy performance targets while respecting conceptual rules for an architectural style.

## Method

### *The GPM setup*

The interactive GPM setup in the case example of this paper followed the method described in Lauridsen and Petersen (2014). Rhinoceros (2017) was used as the architectural CAD tool for design of the single-family house. The Rhinoceros model of the single-family house was parameterised using Grasshopper (2017). Each thermal zone in the parameterised geometric Rhinoceros model was individually and independently linked to the BEM tool ICEbear (Lauridsen and Petersen, 2014), the solar algorithm Viper (DIVA-for-Rhino, 2017), and the daylight calculation tool DIVA-for-Rhino (2017). This enabled integrated climate-based daylight and thermal performance simulations of the modelled house, i.e. to simulate electrical lighting control as a function of the daylight level. Finally, the model was linked to the optimisation tool Galapagos (2017) which facilitates the *generative* part of GPM while respecting the user-defined inputs. The overview of the GPM setup, see Lauridsen and Petersen (2014).

### *Architectural rules of typical Danish detached single-family homes*

Successful implementation of GPM seems to rely on a meaningful interactive link between the architect and GPM input and output. By analysing the historical development of the typical Danish detached single-family home, this section seeks to identify a set of long lasting architectural traits – or “rules” – which also can be regarded as valid for todays’ design practice. These rules are used to parameterise an architectural CAD model of a home to obtain a more practice-oriented example of how GPM can be used to help designers meet low-energy performance targets while respecting conceptual rules for an architectural style.

The aesthetic and functional traits of todays’ detached single-family homes seem to draw upon traditions from three overlapping time periods with distinctive different styles and trends. A brief historic background for the definition of these styles is given in the following. Focus is on describing traits in external appearance, the plan geometry, and how these may influence each other. Figure 1 sum up the historical background of todays’ prevailing architectural styles in Danish single-family homes in pictures, and briefly outline the architectural rules that seem to be prevailing for the styles – rules that could be used for GPM in an architectural CAD tool.

The style *Classism* (Figure 1 top) is based on traits from the Patrician villas (1860-1930) and the Master Mason villas (1910-1930) which have an external appearance characterised by symmetry and rhythm in window placement, the use of many mullions, bay windows, porches, cornices, and high quality materials (Lind and Møller, 2014) (Hede, 2008a). The functional layout is also characterised by symmetry around a dual axis. The Patrician villa has an extravagant ceiling height and a high prevalence of ornamentation which the later Master Mason villa did not have. Furthermore, the original Master Mason villas have no bathroom or toilet inside the house.

The style *Functionalism* (Figure 1 middle) can be defined by the traits from the Bungalows (1920-1940) and the Funkis villas (1930’ies). The external expression is simple and clear, with no cornices and hardly any ornamentation. Windows and doors are located freely in the facade with respect to functional requirements such as light or view out rather than respect for symmetry and rhythm. Most windows are squared with slim or no mullions, but some were round to break the angular look. There are almost always windows in the

façade corners. The Bungalow has sloped roofs and a pronounced overhang while the Funkis villas have flat roofs and no overhangs. The Funkis villa façade is often plastered and basically stripped from ornamentation whereas the Bungalow is made of yellow brickworks with simple details such as patterns made of different coloured bricks. While the Bungalow often has a single-floor quadratic floor plan symmetrically arranged around a chimney, the Funkis villa allows the floor plan to be asymmetric if it would fit the everyday life of the residents (Jensen, 2007). Furthermore, the Funkis villa has more rooms, including a big living room and smaller work-related rooms (Thorsen and Degnbol, 2008). Many of the Funkis Villas has a first floor which was found very functional because upstairs rooms do not have any sloped walls due to the cubic shape and flat roofed building form. Living rooms, balconies and entrance to the garden are often placed to the south to enable the residents to enjoy the sun in these primary housing functions. The layout of houses from the *functionalism* period included bathroom, toilet and central heating.

Original villas	Todays' styles	Architectural rules	
Patrician 	Master Mason 	Classism 	Symmetry in window placement. Mullions in the windows. No significant overhang. Decorations on the façade allowed. Often bay windows, balconies and halfhipped roof with dormer. Symmetric plan around an double-axis
Funkis 	Bungalow 	Functionalism 	Windows are located with respect to indoor functional requirements. No mullions in windows. The façade is flush, monochrome in color with no decorations. Flat or very small roof slope. May have overhang. The plan may be asymmetric if functional.
State Loan 	Standard 	Standard House 	Windows are located with respect to indoor functional requirements. No mullions in windows. Sloped roof. Often a significant overhang. The façade is with no ornamentation. Functional rather than symmetric plan.

Figure 1. Todays' prevailing architectural styles and rules in Danish single-family homes.

The style *Standard House* (Figure 1) emerged from the style of the State Loan houses (1938-1958) which is considered a simplified version of the Master Mason Villa (Hede, 2008b). The external appearance is walls of red bricks with wood in top of the gables, and simple pitched roof which often creates an overhang. Windows with no mullions were placed according to function (as in the style *functionalism*); they often have big windows facing the backyard (private areas), and smaller high-placed windows towards the street (public area). The plan areas is relatively small for the time (less than 100 m<sup>2</sup>), and had therefore room geometries inspired by the style *functionalism*; living room and secondary are connected directly without any corridors to maximize functionality of the scarce space. The room height was relatively low compared to earlier styles but a more spacious feeling was sometimes achieved by letting the ceiling follow the slope of the roof. All State Loan houses have a bathroom and a toilet. In the period 1960-1980, many families wanted to move from the cities and into the suburbs. This led to a mass production of *Standard Houses* in this period; approx. 40 % of detached single-family houses in the current Danish building stock are from this period (Statistics Denmark, 2016). These houses were 'catalogue products' i.e.

not designed for the specific user or site but they are a rather universal in terms of function (Hede, 2008c). They were also rather cheap and fast to build as they were made primarily from prefabricated elements. The external appearance and window placement is quite similar to the *State Loan House* but the plan area was larger and varied in geometry. The larger and sometimes more diverse geometries often resulted in the need for less functional transportation areas.

### Case example

The design of a new house in the style *Functionalism* (see Figure 1) is chosen to illustrate interactive GPM. The example is kept simple: the floor plan is fixed according to Figure 2, while window area, window placement, and overhang are parameters that may vary according to simple architectural rules defined for two different types of façade ("A" and "B" in Figure 2). Two different set of rules were investigated: Scenario 1 has no architectural rules attached to the window geometry and placement parameters, while the window geometry and placement parameters in Scenario 2 are constrained by the user to follow the architectural rules identified for the style *Functionalism*. See Figure 2 for details. In both scenarios, the home had highly insulated constructions ( $U<0.15 \text{ W}/(\text{m}^2\text{K})$ ), low-energy windows ( $U_g=0.53 \text{ W}/(\text{m}^2\text{K})$ , SHGC=0.5,  $U_f=1.38 \text{ W}/(\text{m}^2\text{K})$ , frame width=0.054 m,  $\Psi=0.06$ ), mechanical ventilation with heat recovery ( $0.3 \text{ l/s/m}^2$ , SFP=800 J/m<sup>3</sup>, HR=0.85), and low infiltration rate ( $0.1 \text{ l/s/m}^2$ ).

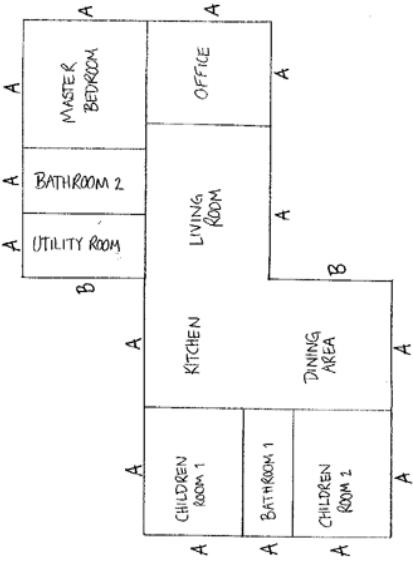
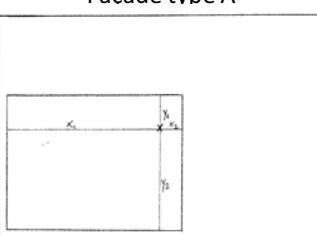
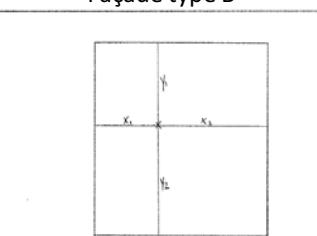
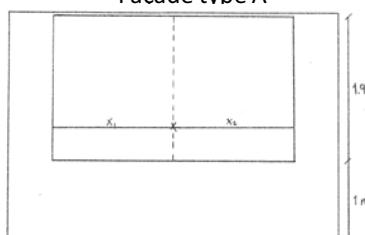
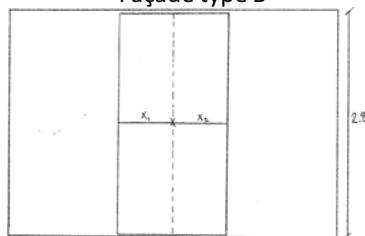
Floor	Scenario 1 (no rules)	Scenario 2 (functionalism)
 <p>"A" and "B" refers to the façade types</p>	<p>Façade type A</p>  <p>Window may vary in size and placement.</p> <p>Façade type B</p>  <p>Window may vary in size and placement.</p>	<p>Façade type A</p>  <p>Fixed parapet (1.0 m). Fixed window height (1.9 m). Window always centered in wall (<math>x_1=x_2</math>). Only width may vary.</p> <p>Façade type B</p>  <p>Fixed window height (2.8 m). Window always centered in wall (<math>x_1=x_2</math>). Only width may vary.</p>

Figure 2. Case example. Left: The floor plan. Right: Architectural rules for the variable parameters.

The GPM was run for both scenarios with the objective to minimise primary energy use for building operation, e.g. space heating, mechanical ventilation and cooling, circulation pumps and domestic hot water, as defined in the European Performance of Buildings Directive (EPBD, 2010). The minimisation was constrained by an indoor operative temperature requirement of maximum 100 hours above 27 °C, and maximum 25 hours above 28 °C per year. Furthermore, the glazed area of a window cannot be less than 15 % compared to the floor area of the room to ensure a minimum of daylight. The described thermal and daylight constraints are analogue to the recommendations provided in the Danish building regulation (BR15, 2015).

## Results and discussion

Table 1 shows the architectural solution spaces for each room in both scenarios, i.e. the number of solutions for each room that ended up fulfilling the thermal and daylight constraints while the GPM minimised the energy use. In principle, each solution consists of a unique combination of window geometry, window placement, and overhang.

Table 1. Architectural solution spaces and their energy performance.

	Scenario 1 (No rules)		Scenao 2 (functionalism)	
	Solutions (-)	Energy use (kWh/m <sup>2</sup> /yr.)	Solutions (-)	Energy use (kWh/m <sup>2</sup> /yr.)
Living room	678	28.7±1.0	24	27.0±0.8
Master bedroom	686	33.6±0.9	138	35.0±0.9
Room 1	124	30.2±1.3	32	31.2±1.2
Room 2	342	38.0±1.0	58	39.1±1.2
Bathroom 1	326	35.4±0.2	90	36.0±0.2
Bathroom 2	408	39.8±0.6	185	40.4±0.7
Office	46	36.7±1.7	8	38.2±0.6
Utility room	517	51.1±1.0	19	54.0±0.6
TOTAL (average)	-	36.7±6.5	-	37.6±7.4

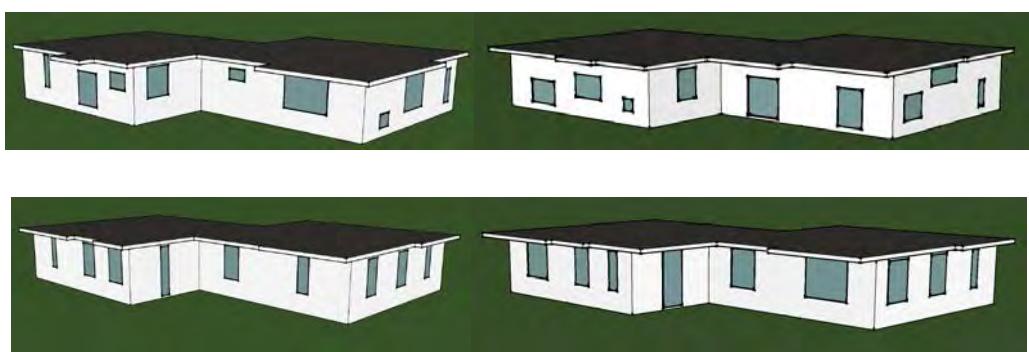


Figure 3. Solutions with different architectural expression. Top: scenario 1. Bottom: Scenario 2.

The architectural rules added in Scenario 2 had a significant influence on the amount of possible solutions generated by the GPM, and they also increased the average energy consumption slightly. When browsing through the possible solutions on room level, many of them are only slightly different in architectural expression but there are also solutions with different architectural expressions to choose from as illustrated in Figure 3. In general, the typical façade solution in Scenario 2 has a calm rhythm, is readable, and has a sense of an

architectural idea in the external appearance whereas the more random window placement and size of a typical solution in Scenario 1 seems to be rather coincidental and without the sense of an architectural idea in its external expression.

The average energy performance of the rooms in the population of possible solutions could probably be lowered even further by increasing the amount of insulation and decreasing the infiltration rate. However, changing these energy-related boundary conditions would also remove and/or add possible solutions to the architectural solution space. Furthermore, the geometry of the overhang is rather random in both scenarios and could from an architectural point of view maybe benefit from following a certain line of rules. This would also affect the architectural solution space generated by the GPM.

## Conclusion

The example of this paper demonstrates that an interactive GPM concept is able to automatically generate numerous of solutions with minimised energy use while respecting user-defined requirements to the quality of the thermal indoor climate and daylight conditions – but also while following certain user-defined architectural rules. The designer may now choose one of the generated solutions to refine further, or to go back to the GPM, revise the requirements and rules, and generate a new set of possible solutions to choose from. However, new studies are required to assess whether this GPM-based approach is considered useful to practicing designers working on real life building projects.

## References

- Danish Building Regulations (BR15). (2015) Copenhagen: The Danish Ministry of Economic and Business Affairs.
- de Souza, C. B. (2011). Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer. *Automation in Construction*, 22, pp. 112-122.
- DIVA-for-Rhino. (2017). Solemma, US, <http://diva4rhino.com/>
- EPBD. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 December 2010 on the energy consumption of buildings (recast).
- Galapagos. (2017). Rutten, D., Austria, <http://www.grasshopper3d.com> Grasshopper. (2017). Scott Davidson, US, <http://www.grasshopper3d.com/> Green Building Studio. (2017). Autodesk, US, <http://gbs.autodesk.com/GBS/> Hede, M. (2008a). Murermestervillaen. *Bedre bolig*, 4(1), pp. 46-49.
- Hede, M. (2008b). Statslånshuset. *Bedre bolig*, 4(3), pp. 46-51. Hede, M. (2008c). Tyve års typehus. *Bedre bolig*, 4(6), pp. 60-63. Jensen, P. K. (2007). Moderne funkisvilla. *Nye huse*, 3(2), pp. 10-17.
- Lauridsen P.K.B., Petersen S. (2014). Integrating indoor climate, daylight and energy simulations in parametric models and performance-based design. In: *Jensen L.B. and Thompson M.K (eds.) Third International Workshop on Design in Civil and Environmental Engineering*, Kgs. Lyngby, Denmark, 22 – 23 August 2014. Kgs. Lyngby: DTU Tryk.
- Lind, O., Møller, J. (2014). *Alle tiders parcelhuse: 1860-2012*. Copenhagen: Gyldendal. Lipp M., Scherzer D., Wonka P., Wimmer M. (2011). Interactive Modeling of City Layouts using Layers of Procedural Content, *Computer Graphics Forum*, 30, pp. 345-354.
- Lipp M., Wonka P., Wimmer M. (2008). Interactive Visual Editing of Grammars for Procedural Architecture, *ACM Transactions on Graphics*, 27(3), pp. 1-10.
- Merrell P., Schkufza E., Li Z., Agrawala M., Koltun V. (2011). Interactive Furniture Layout Using Interior Design Guidelines, *ACM Transaction on Graphics*, 30, pp. 87:1-10.
- Openstudio. (2017). NREL, US, <https://www.openstudio.net/>
- Oxman R. (2006). Re-thinking digital design. *WIT Transactions on The Built Environment*, 90, pp. 239-247.
- Petersen S., Bryder J., Levinsen K., Strunge J. (2014). Method for integrating simulation-based support in the building design process. In: *Jensen L.B. and Thompson M.K (eds.) Third International Workshop on Design in Civil and Environmental Engineering*, Kgs. Lyngby, Denmark, 22 – 23 August 2014. Kgs. Lyngby: DTU Tryk.

- Petersen, S., Svendsen S. (2010). Method and simulation program for informed decisions in the early stages of building design. *Energy and Buildings*, 42 (7), pp. 1113-1119.
- Radfort, A.D., J.S. Gero. (1980). Tradeoff diagrams for the integrated design of the physical environment in buildings, *Building and Environment*, 15(1), pp. 3-15.
- Rhinoseros. (2014). Robert McNeel & Associates, US, <http://www.rhino3d.com/>
- Statistics Denmark (2016). Statistisk Årbog 2016. 120<sup>th</sup> Edition. Copenhagen: Rosendahls.
- Thorsen, P.M., Degnbol, L. (2008). Funkisvilla og bungalow. *Berre bolig*, 4(2), pp. 20-29.
- Ullrich T., Silva N., Eggeling E., Fellner D.W. (2013). Generative modeling and numerical optimization for energy efficient buildings. In: *IECON 2013 - 39th Annual Conference of the IEEE*, Vienna, Austria, 10 – 13 November 2013.
- Vanegas C.A., Aliaga D.G., Wonka P., Müller P., Waddell P., Watson B. (2010). Modelling the Appearance and Behaviour of Urban Spaces, *Computer Graphics Forum*, 29, pp. 25-42.
- Watson B., Wonka P. (2008). Procedural Methods for Urban Modeling, *IEEE Computer Graphics and Applications*, 28(3), pp. 16-17.
- Østergård, T., Jensen, R. L., Maagaard, S. (2016). Building simulations supporting decision making in early design: A review. *Renewable & Sustainable Energy Reviews*, 61, pp. 187-201.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Frames and Finishes: The Evolution of a Performance Based Aesthetic

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**Abstract:** New working patterns, changing legislation, developing technology and economic uncertainty has pushed designers and clients to think more collaboratively about how commercial buildings are designed. This paper describes the evolution of a performance driven aesthetic through designed and built by Allford Hall Monaghan Morris architects. The narrative uses mixed POE data and environmental modelling to discuss integrated performance metrics including energy, productivity and economic return. A study of the economy, robustness, flexibility and longevity of Victorian warehouses led to the development of a series of modern incarnations. A suite of design techniques is used, including: integrated structure and services in a speculative office with minimal applied finishes, re-purposed flexible structures, sophisticated engineering and control mechanisms in new factory-style offices, all integrated to deliver optimum performance. This thinking is explored in three design stage buildings that share a further development of this approach and aesthetic. The buildings are in London, Bristol and Salford. Discussion focusses on how resource efficiency, low energy consumption and user control has driven the development of this aesthetic. Conclusions include the need for greater design collaboration combined with articulation of economic benefits to deliver high performance integrated architecture.

**Keywords:** Aesthetics, Performance, Energy, Resources, Integration.

### Introduction

The market for commercial office space is increasingly competitive, with a recent flattening of demand in London particularly, the competition for tenants is fierce ([www.rics.org](http://www.rics.org)). Commercial buildings account for some 26% of UK's total CO<sub>2</sub> emissions (p. 110. [www.theccc.org.uk](http://www.theccc.org.uk)) and while CO<sub>2</sub> emissions are the focus of the building regulations, the metrics defining performance are shifting towards a more complex measure of occupant focussed performance like wellbeing or productivity (World Green Building Council, 2014).

With a more rounded view of the environmental impacts of buildings and within the budgetary and supply chain pressures of the commercial office market, Allford Hall Monaghan Morris architects (AHMM) have developed an expressive architectural approach focussing on energy, daylight, user interaction, resource use, quick turnaround of tenancies, low construction waste, maximised comfort and return on investment (Robertson and Idzikowski-Perez, 2016).

This paper describes the development of an aesthetic for commercial office space driven by these various performance criteria based on the historical precedent of urban warehouses. Warehouses are re-purposed throughout the UK to house creative and office based industries. The qualities that allow this functional adaptability and attract potential tenants include low capital and operational costs, tall ceilings, large daylit volumes, the ability to condition space passively through use of thermal mass and large span, flexible floor plates.

The following case studies illustrate the evolving aesthetic through five complete or completing buildings focussing on an aspect of performance.

### **Tooley Street – Energy**

160 Tooley Street in South London is a six storey, 18,600m<sup>2</sup>, part new build, part refurbished mixed-use speculative development completed in 2008 that embodies progressive thinking about commercial architecture.

The brief was to embrace sustainability, enhance the character of the existing buildings and maximise net lettable area. Focus was given to utilising modern methods of construction where high levels of prefabrication would lead to cost efficiencies and waste reduction.



Figure 1. New façade.



Figure 2. Exposed mass.

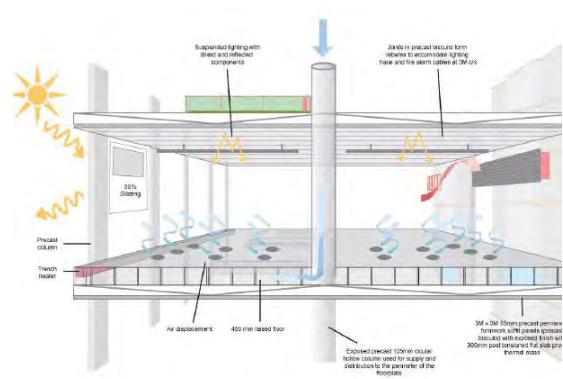


Figure 3. Illustrated servicing strategy.

The materiality of the new facades responds to the urban context, materials are hard and glazing ratios are driven by solar gains (figure 1). Internally, a new offices aesthetic becomes apparent, driven by the building's energy strategy. Exposed concrete takes advantage of the thermal capacity of the material by absorbing daytime heat gains. Lighting and other services are exposed and carefully detailed, adding to the new aesthetic (figure 2).

A displacement air conditioning system with centralised extract removes grilles from the ceilings. 'Structural ducts' deliver air to underfloor plenums. Air travels down from roof level so as the capacity of air required reduces, the structural need increases (figure 3). This reduces riser space in the core and integrates architecture, structure and services.

Tooley Street represents an aesthetic driven by energy performance, challenging the prevailing aesthetic of suspended lightweight aluminium ceilings. The space delivers a commercially attractive internal environment (it is fully let) integrated building physics, structure, services and architectural expression.

### **Morelands - Indoor Environmental Quality (IEQ)**

Morelands Rooftop is a part new-build, part re-use BREEAM Outstanding penthouse office on top of former warehouses on Old Street, London. The structurally light new 5<sup>th</sup> floor complements the heavyweight refurbished 4<sup>th</sup> floor. Both are large volumes that maximise natural light and ventilation and minimise the use of applied materials.

The façades were insulated and rendered, unifying the external appearance of the two floors and improving the thermal performance (figure 4). The space is naturally ventilated via occupant controlled windows at low level on the perimeter walls and at high level to central

light wells (figure 5). The exposed concrete soffit on the 4th floor helps with night cooling and external blinds are linked to UV sensors reduce external gains.



Figure 4. External render.



Figure 5. Interior.

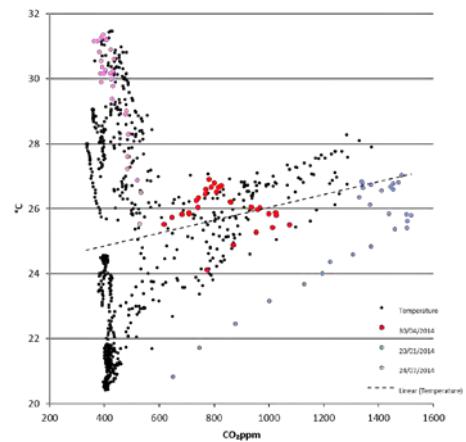


Figure 6. Indoor air quality.

Temperature monitoring shows that the spaces are generally much warmer than they were designed to be. Figure 6 shows three different weeks of data comparing CO<sub>2</sub> concentrations with internal air temperatures. Occupants appear to open windows when temperatures reach around 25-26°C regardless of CO<sub>2</sub> concentrations. Reducing concentrations of internal pollutants requires earlier, lower temperature engagement with windows and ventilation (Robertson et al, 2015). Management strategies have been developed to mitigate this.

The environmental approach to Morelands drives the aesthetic but temperatures are generally outside of CIBSE standards. A pleasant space means happier occupants but needs managed to deliver comfortable conditions (Idzikowski-Perez, 2015). A performance based aesthetic must make occupant led management strategies explicit.

### ***Tea Building - Economics***

The Tea building is the reuse of an existing warehouse building in Shoreditch, London (figure 7). Initially approached as a demolish and rebuild project, due to an economic slump the design approach shifted towards a cheaper, more flexible solution. The finished building houses a variety of commercial spaces and has become a byword for economic regeneration of existing buildings.

The aesthetic in this case was driven by economics, both capital expenditure and return on investment providing a range of spaces that were not only cheap to build but cheap to let. Acknowledging that the building was refurbished in a changing market – lease rates trebled in the first ten years of occupation – the building was designed with ease of change and evolution built in.

Ongoing improvements include window upgrades, through wall controllable background ventilation, solar control blinds and insulation of the facades, lighting control systems and night-time purging. An active hybrid system was also implemented through installation of a high efficiency rooftop heat exchanger which provides a hot & cold water thermal loop through the building that can be connected to provide heating, cooling (or both) to any unit.



Figure 7. The Tea building.



Figure 8. Interior at the Tea building

The Tea building represents an aesthetic driven by economic performance. Refurbishment of the existing building has brought back into economic use a perfectly good warehouse building (figure 8). The rough and ready aesthetic allows for gradual upgrade of the building as rental value increases and market expectation changes.

#### ***University of Amsterdam - Low resource use***

The University of Amsterdam project is the regeneration of a post-war campus in central Amsterdam. The project involved the re-invention of an existing building (figure 9), with substantial structural alterations and replacement of the facades.

AHMM's approach focussed on the movement of people around, through and into the building, integrating the structure into the streetscape. New public rooms encourage the non-university users into the building (figure 11) and newly formed colour-coded mini atria help orientate building users and provide opportunity for social interaction.



Figure 9. Retained concrete

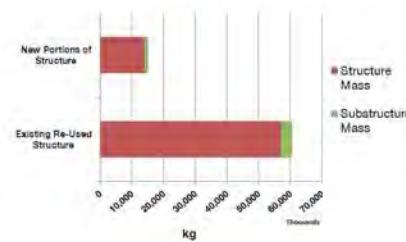


Figure 10. Retained mass.



Figure 11. New public room and low energy concrete.

Re-using the existing concrete frame meant that the most embodied-energy intensive, and massive, part of the building was already in place (figure 10). To further reduce embodied energy, new concrete structural components used cement replacement with GGBS (ground granulated blast furnace slag) content of over 67%.

The heat capacity of the existing frame is used with night ventilation as a thermal store to reduce the need for mechanical cooling. In addition to the embodied and operational energy savings, retaining the frame and utilising off-site manufacturing helped reduce construction waste, saving 60,000 tonnes of rubble, and the resultant thousands of tipper truck journeys across the city.

The University of Amsterdam represents a project that has an aesthetic driven by resource reduction and the retained structure. The existing frame is the structure, the internal finish and is engaged in the energy performance of the building.

### ***White Collar Factory - Integration***

As a naturally-ventilated sixteen storey spec-office with a focus on smart servicing, flexibility and adaptation to future uses and climate, the White Collar Factory (WCF) at Old Street Yard is a bold iteration of the new commercial aesthetic. Featuring long spans, flexible floor plates, operable windows, generous volumes and robust construction, the climate control benefits of the building's passive design eliminates the need for air conditioning.



Figure 12. WCF Exterior.



Figure 13. WCF Interior.

The WCF uses Concrete Core Cooling (CCC) as its primary method of conditioning the office environment. The cooled slabs provide radiant cooling and thermal mass to absorb internal gains. The design principles are an evolution of the warehouse derived characteristics: high ceilings, a passive façade with openable windows that respond to orientation through varying the amount of shading, activated thermal mass though the CCC, highly flexible floor plates and a deep plan to maximise opportunities for adaptation.

The relatively low technology approach of the environmental strategy – which relies on simple building physics – is combined with a high-tech series of data display systems that allow building users to interact and control their space. A simple traffic light system that lets occupants know when the building is in hybrid mode and windows should be opened. The

relationship between architecture, controls, technology and the physical systems drive the integrated aesthetics of the building system.

### Three New Buildings

#### *Manchester - Regeneration*

New Bailey Square in Salford will provide flexible working environments referencing the spirit of Salford's industry. It will be a 21st century warehouse for work (figure 14). The performance principles of this building are to maximise active frontages, create a unique identity, clean and open floor plates and maximised daylight and views out. This is expressed through a standard and efficient material palette that expresses materiality honestly, intelligently and sustainably.



Figure 14. Exterior.

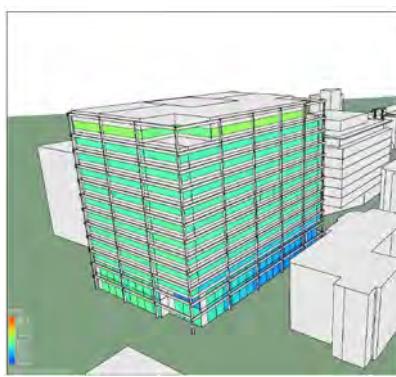


Figure 15. Solar Gains assessment.



Figure 16. Elevation.

The steel structure is exposed and held 600mm from the facade. This performs several functions. It provides solar shading in a market that demands a maximally glazed envelope (although this building is at around 55% glazed due to included solid spandrel panels), which in turn means higher G-Values are possible, reducing glass costs and improving visible light transmittance. The frame, its construction and the shadows it casts becomes the main architectural expression of the elevation allowing the 'skin' to be a much more economical component than would be otherwise possible. Cold bridges are dealt with using resin plates at the point of penetration. Our energy model was analysed to explore the aesthetics' relationship to performance criteria. The external steel frame helps to reduce solar gains by 10% while not significantly impacting on daylight levels or views out (figure 15).

Servicing systems are expressed in the interior and openable windows improve occupant comfort. Minimal applied finishes reduce resource use (figure 16). The street frontage is activated by a mix of complementary uses and each floor level enjoys generous private outside decks.

The aesthetic of simple, cost effective flexible floor plates is reflected in benefits in energy consumption and flexibility. The developing masterplan demands quick and economical construction, this approach delivers a building that can meet these requirements.

#### *London - Efficiency*

This new build speculative office forms part of an emerging masterplan in London. The building comprises of 10 storeys of office use above ground floor of retail and reception. An

external steel frame expression (figure 17) has been pursued, creating an architecture that reflects how the building is made and functions. This results in a universal building that is economical and performs significantly better than briefed environmental targets (figure 18).



Figure 17. Elevation.



Figure 18. Interior.



Figure 19. Energy Savings.

Early studies investigated opening window provision and findings suggested that there were significant benefits to incorporating opening windows as part of the controllable aesthetic; energy reductions were potentially as high as 90% (figure 19). The steel frame performs a similar range of functions as New Bailey Square. The shading effects of the frame on this project are a near 10% reduction in gains.

This aesthetic is an expression of efficient, lean, low resource use which drives low energy in operation, however the opportunities of such an approach require explicit statement in management guidance.

#### ***Bristol - Integrated Aesthetic***

Assembly in Bristol is a mixed-use scheme on Bristol's floating harbour awarded planning permission in early 2017. The proposals provide new flexible office space for up to 3,000 people. Sustainability has been an integral part of the design process, emphasis has been placed on passive design measures.



Figure 20. Exterior.

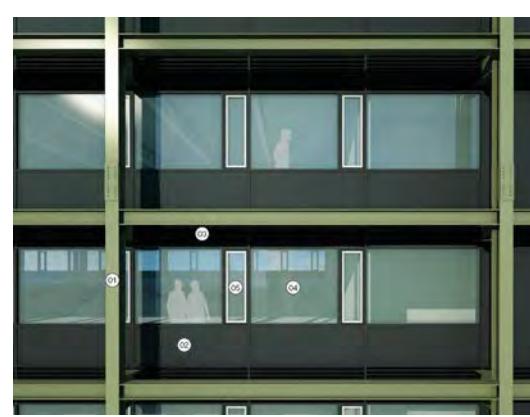


Figure 21. Elevation.

The strategic thinking behind this project has developed to include specific architectural expression of materiality, construction techniques and environmental performance (figure 20). The building again uses an exposed steel frame and develops this aesthetic with an

exploration of dry construction techniques, CLT floor plates, and visually expressed opening windows (figure 21).

The architectural aesthetic reflects these multi-faceted performance aspirations and allows for flexibility in the design to aim for multi-faceted performance targets. Adaptability to climate, function and servicing, low waste and unitised construction and occupant control.

## Discussion

The deliberate, strong expression of construction materials and methods and integrated environmental strategies represents a departure from mainstream commercial building design, where identity is typically defined by a shallow wrap-around skin of limited visual interest.

Expressing the structural elements reflects the nature of manufacture and fabrication of a semi-industrial aesthetic, a language of construction that is appropriate to the 21st century urban workplace. Internally, a language of limited applied finishes, occupant controlled environments with open, simple floor plates creates a connection between user, architecture and environment.

The strong character of such buildings is defined by multiple functions and performance metrics of energy, economy, low resource use, flexibility and adaption. Internal spaces can change and evolve whilst being comfortable, productive and efficient now and in the future.

In complex urban environments with many conflicting performance targets spanning economy, environment and human impact, an integrated aesthetic than synthesises and expresses these with simplicity, economy and delight has emerged.

## References

- Idzikowski-Perez, I (2015). Temperature and Productivity in Free Running Office Buildings: A Case Study In Central London. Masters in Environmental Design and engineering, University College London.
- Robertson, C and Idzikowski-Perez, I (2016). In Control – Thermal Comfort and Productivity, CIBSE Journal, September 2016.
- Robertson, C., Mumovic, D., Ahn Ding, Q., Fitzpatrick, I., Crawley, N., (2015). Productivity and Investment in a Naturally Ventilated Lean Office Development. In: CIBSE Technical Symposium. London, 2015.
- World Green Building Council (2014). Health, Wellbeing & Productivity in Offices The next chapter for green building, 2014.
- [www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/604327/2016\\_Provisional\\_employment\\_statistics\\_one\\_page\\_summary.pdf](http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/604327/2016_Provisional_employment_statistics_one_page_summary.pdf), accessed 14/04/2017.
- [www.rics.org/Global/RICS\\_UK\\_Commercial\\_Property\\_Market\\_Survey\\_Q1\\_2017.pdf](http://www.rics.org/Global/RICS_UK_Commercial_Property_Market_Survey_Q1_2017.pdf), accessed 29/05/2017.
- [www.theccc.org.uk/wp-content/uploads/2013/06/CCC-Prog-Rep\\_Chap3\\_singles\\_web\\_1.pdf](http://www.theccc.org.uk/wp-content/uploads/2013/06/CCC-Prog-Rep_Chap3_singles_web_1.pdf) , accessed 29/05/2017.
- [www.ukgbc.org/sites/default/files/Health%2520Wellbeing%2520and%2520Productivity%2520in%2520Offices%2520-%2520The%2520next%2520chapter%2520for%2520green%2520building%2520Full%2520Report\\_0.pdf](http://www.ukgbc.org/sites/default/files/Health%2520Wellbeing%2520and%2520Productivity%2520in%2520Offices%2520-%2520The%2520next%2520chapter%2520for%2520green%2520building%2520Full%2520Report_0.pdf), accessed 14/04/2017.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Presence of energy concerns in the conceptual approach of Fernand Pouillon in the 50s: The Case Study of Pouillon's Housing Estate in Algiers

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**Abstract:** After the Second World War, several responses were proposed through the CIAM charters about the future of mass construction of housing. It was through standardization and the use of new materials as well as industrialized techniques and construction processes similar to the mass production system. Sustainable development and the reduction of energy consumption were not their primary concerns. In the 1990s, energy concerns were part of the quality problems of buildings in the architectural design. However, the solutions proposed were mostly isolated and purely technical. Meanwhile, in the 1950s, Fernand Pouillon introduced new ideas and a new vision concerning the future of the mass construction of housing, bearing in mind the built environment and the durability of the material. He developed a design process based on an industrialization of construction processes by *simple element* instead of *heavy prefabrication* of the housing. Through the analysis of the housing estate of Fernand Pouillon's "*Climat de France*", we will try to show his modern vision of the future of housing and the presence of energy concerns in his conceptual approach.

**Keywords:** Sustainable development, Fernand Pouillon, Climat de France, industrialization by simple element

### Introduction

The philosophy of sustainable development applied to architecture is based on the design of a sustainable building that respects the environment through its constructive process, building materials and conceptual approach. After the Second World War, a major acceleration in the reconstruction process began to rebuild what the war had demolished. Heavy industrialization was the absolute answer for modern architects of the time. However, this industrializing had negative repercussions on the natural and built environment. In 1987, in the report "Our Common Future", European Commissioner Harlem Brundtland set up a new concept: "Sustainable Development", aimed at "reducing social inequalities, while preserving the environment in a sustainable manner, Economic development". Therefore, it is a development that "must meet the needs of present generations without compromising those of future generations" (Tolba & Biswas, 1991).

Meanwhile, Fernand Pouillon introduced new ideas and a new vision for the future of the construction of mass housing, which were criticized by most of his colleagues. He called into question what the masters of the modern movement saw as the only way towards modern architecture. He concretized his ideas thanks to Jacques Chevalier newly elected mayor of Algiers at the time, who entrusted him with the construction of more than 7000 apartments divided into three complexes: Diar Es Saada, Diar El Mahçoul and Climat de France.

He resumed all the issues that were discussed by the modern movement. The most fundamental is the question of mass production of housing; "*I struggled alone so that the neglected part of the architecture finds life, spirit and love*" (Pouillon, 1968).

We will try in this manuscript to draw a small panorama on the development of post-war architecture until the emergence of the notion of sustainable development. In parallel, we will show the new vision of Pouillon in the 1950s for the future of the massive construction of housing that is concerned with the impact of architecture on the natural and built environment, as well as on the inhabitant.

### **Panorama on the development of the architecture since the post-war period until the emergence of the notion of sustainable development**

The housing crisis of the 1950s favoured the borrowing of the industrialization way to deal with the quantity problem. The industrialization of the building began after the first world war of 1914-1918 with some pioneers, architects and builders, impressed by the results achieved in the automotive and aeronautical industry such as Walter Gropius, Voisin (constructor of airplane), Henri Sauvage and Jean Prouvé (builders), Le Corbusier and Marcel Lods (*Sociétés des architectes préfabriquateurs*), Beaudoin and Auguste Perret. (Chemillier, 2002)

However, the disastrous situation of France in 1945 after the second world war accelerated the process of industrialization of the building. The solution for building a lot, quickly, and inexpensively was the factory prefabrication such as in the automotive industry with reinforced concrete as the preferred material. This need of building obliged the architects of the modern movement to find other alternatives. This situation has favoured the search for new paradigms that go along with this industrialization. Le Corbusier invented the free plan with the constructive system in domino and opposed it to the paralyzed plan resulting from the constructive system in bearing wall (Le Corbusier, 1994).

The success of industrialization in the automotive field is based on the control of the production chain, the large quantity of production, and the continuity of the production process in the same place. In the building, the last two elements were a problem. Despite the large quantity of built housing, they were dispersed in several sites. To solve this problem, the France government launches the ZUP (zones à urbaniser en priorité) which means in English "areas to be urbanized as a priority". It allows to group together a large number of dwellings to be built in a single site to get even closer to the image of automotive industrialization. (Chemillier, 2002). It should be noted that this industrialization was efficient in terms of quantity. The annual production of housing in France rises from 46,000 units in 1951 to 360,000 in 1964 (2002).

In the late 1960s, the demand for housing in France fell sharply, forcing the state to halt major operations. The exchange solution is the grouping of orders (in 1969 a threshold of 200 dwellings was imposed for the HLM<sup>1</sup>) and the use of the models (a model project is established by an architect and contractor who is approved by the state and used to ensure a large housing order).

However, the urban forms generated by this type of construction has begun to be rejected due to a monotonous architecture of models in the early 1970s. The large amount of housing generated by industrialization processes required quality management as in the automotive industry. Therefore, the architects have started talking about quality, which has

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<sup>1</sup> "Habitation à loyer modéré" which means in English "Low-income housing"

become an important criterion just as quantity. Once again, the quality management of the manufacturing industry was taken as a model to develop quality measurement approaches in the building sector (Gann, Salter, & Whyte, 2003). The building is still considered as an industrial product.

The end of the 80s and the early 90s stands out for the concept of sustainable development and respect for the environment in construction. It has been found that the industrialization of the building has created problems with architectural quality, integration into the context and respect for the built environment. In the last 50 years, we were only concerned with the quantity of the building while neglecting its impact on the environment.

A return to the vernacular architecture has become very encouraged to rediscover the noble, sustainable, and ecological materials, as well as an architecture that respect context ,and the built environment.

At the same time, in an industrial vision, researchers propose technological approaches to make building sustainable (Kibert, J. C, 2016). However, these steps are very costly. As a result, ecology and sustainable development have become trademarks. These approaches concerned only parts or components of the building following an industrial vision. These are mostly very expensive technological solutions that have been integrated into the building. These solutions rely on the principle that the overall management of the building is the sum of the management of its various parts. While the architectural whole is more than the sum of its parts (Dehan. P., 2009).

Whereas back in the 1950s there was Fernand Pouillon, an architect who found sustainable and ecological solutions at the time to respond to the housing crisis. While his colleagues saw the future of construction in heavy industrialization, he returned to the architecture of traditional cities. He has opted for the industrialization of construction processes by simple element (Barazzetta, 2001) of noble and durable materials like dressed stone and terracotta. He has developed a design process to reduce the ultimate deadline and cost of construction with remarkable architectural quality. It had even become a slogan for him. For the operation of 200 housing units in Aix en Provence in France, he said that I will build 200 homes in 200 days for 200 million francs.

Even though there was no mention of sustainable development at the time, Pouillon was concerned about the impact of its architecture on the built environment and its inhabitants. The three pillars of sustainable development are present in the architecture of Pouillon; Reducing social inequalities by building monuments for the poor and delivering equipped homes in the Diar Es Saada operation; Preserving the environment in a sustainable manner by building with noble and sustainable materials while respecting the built environment; And finally build at a lower cost and in a short time without constraint on economic development.

### **Climat de France**

Climat de France is the third and last housing estate built by Pouillon in Algiers between 1954 and 1957 (figure 1) in the working-class district of Bab-el-Oued. The complex is located on the heights of Algiers with views on the sea, on sites selected exclusively by Fernand Pouillon. The complex is part of a political project for the equality of Muslim and European citizens. They are part of an HLM program to make up for the housing deficit in the capital, on one hand; and they are aimed at getting rid of the slums in Algiers and at giving a new urban image to the capital, on the other hand.



Figure 1 : Climat de France ground plan

Source : « la fondation des pierres sauvages de Fernand Pouillon

We will try to show in this part the presence of the three principles of sustainable development in the architecture of Pouillon in the fifties, when at that time; worrying about the environment and the durability of the materials of construction was not an important issue.

### ***Reducing social inequalities***

Reducing social inequalities, as it is the first pillar of sustainable development, it was also one of the most important objectives for Pouillon. He is known as a social and humanist architect. "I had focused my life on the social role of architecture: first of all, to build cities for the improvement of the condition of men, putting comfort and beauty within everyone's reach" (Pouillon, 1968). He was able to concretize his vision by building monuments for the poor of Algeria of the 50s, which was a French colonization at the time, to try to equalize between the Europeans and the Muslims of Algeria. It is the dignity of men that interests him. He said in his "memoires": "I had only one goal, one only: to impose by number and quality, a form of human and generous architecture, to create an example." (1968)

### ***The respect of the environment by building in a perennial way***

The second principle that concerns the respect of the environment by building in a perennial way is present in the architecture of Pouillon. His preference for dressed stone and terracotta brick as building materials avoids the additional costs of coating and maintenance as in reinforced concrete constructions. In addition, stone is a noble and durable material unlike concrete. He said about this: "I had been interested in materials for a long time. I hated the ugliness of render, the colour of concrete. For me the century of reinforced concrete posed problems of appearance, of surface, of the skin of the building ". (Caruso, 2014)

Pouillon's choice of the stone to solve the housing crisis in the fifties was contrary to common practice, where an overwhelming majority of architects and engineers, supported by administrative and political apparatus, have opted for industrial prefabrication (Lucan, 1996). Even based on the principle of repetition and standardization like his colleagues, Pouillon escapes the monotony and the standard-project which poses the problem of

integration in context. In Climat de France, Pouillon was inspired by the cities of the M'Zab and the Casbah of Algiers, and the fact that there is a single traditional house that repeats itself in the most human aspects, with a maximum of fantasy, without no feeling of boredom or monotony (1996). The complex of Climat de France is designed with the same housing unit that of Diar El Mahçoul. He relied simultaneously on two principles of composition, the principle of bilateral symmetry and the principle of the picturesque.

Moreover, Pouillon has also invested in ventilation mechanism, natural lighting and thermal insulation to reduce the energy consumption of his buildings for the poorest inhabitants of the poor Algeria of the time. Pouillon focused on purely architectural solutions that are durable and passive. Pouillon opted for the closed order to compose his complexes. This conceptual choice consists in the arrangement of buildings around a place to create an interior landscape. Whereas at the time, modern architects abandoned the closed order with the spatial organisation of city blocks and the traditional street, or *rue-corridor* (Caruso, 2014). They opted for the open order based on the hygienist principle and the optimum orientation of the buildings in relation to the sun's path (Lucan, 1996).

We will not dwell on the details that concern the two principals of architectural composition. We will focus instead on bioclimatic advantages of the principle of the closed order.

#### *Natural ventilation*

As far as natural ventilation is concerned, two principals have been implemented: cross ventilation (through flats) and chimney ventilation.

Cross ventilation is assured as all apartments of Climat de France are through apartments (figure 3) except of a single building where the apartments are separated by a patio in the middle. This design choice highlights the comfort of the inhabitants by the variety of sights and sensations of space even in small rooms.

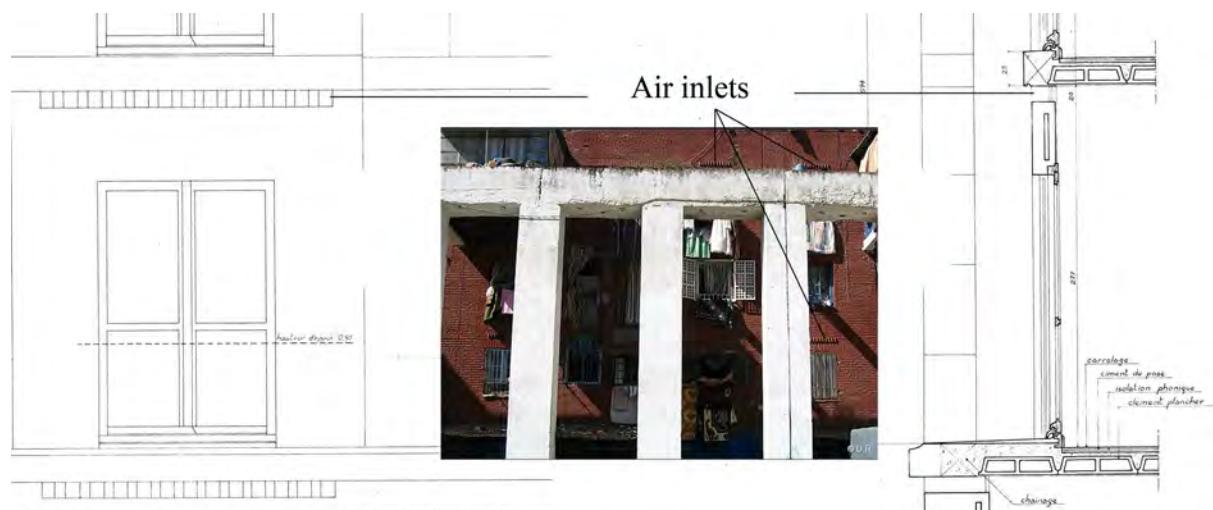


Figure 2: Air inlets in the façade's windows of Climat de France  
Source : « la fondation des pierres sauvages de Fernand » edited by the

While in chimney ventilation, the air moves due to the differences in wind pressure between the façades of the building and the difference in the density depending of its temperature without any mechanical equipment. It is the stack effect (thermal draft) where the air penetrates by the air inlets that Pouillon has laid over the façade's windows (figure 2)

and will be evacuated by the vertical ducts that are placed between the kitchen and the bathroom that Pouillon called "la courrette".

The different squares in the complex of Climat de France allow to reinforce the nocturnal ventilation during the summer by playing the role of the courtyard in a single house (figure 3). During the night, the internal temperature of the rooms surrounding the square rises due to the dissipation of the heat stored in their walls, due to their exposure to the sun during the day. As soon as the windows are opened, the air is renewed automatically. Fresh air in the shaded place is transmitted through the low openings to the inside, thus evacuating hot air through the high openings (stack effect).

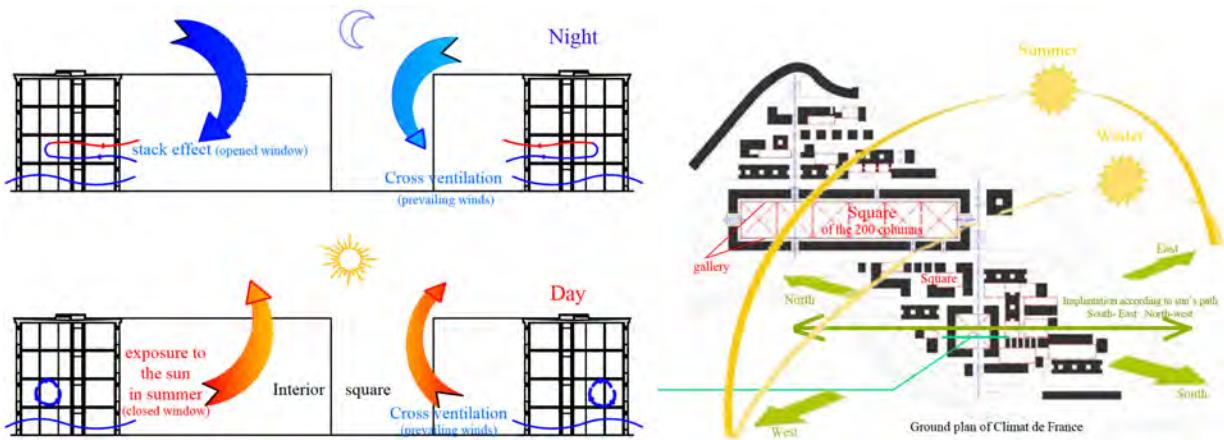


Figure 3: Natural ventilation (cross and chimney ventilation) and lighting in Climat de France

#### *Natural lighting*

Natural lighting is also ensured by the fact that most of the apartments are floor-through apartment, which allows to have windows in all rooms, as well as an implantation of the complex according to sun's path (South-East, North-West)(figure 3).

The desire to control and minimize solar radiation entering the living space in arid zones such as in North Africa, for example, often results in a decrease in natural lighting. The square offers the possibility of reconciling these two contradictory constraints. In the building of the 200 columns (the largest building of Climat de France), Pouillon surrounds the square by a shaded gallery (figure 3) which contributes to reducing the impact of solar rays on the exterior walls of the building.

#### *Thermal insulation*

For thermal insulation, Pouillon takes advantage of the density of the dressed stone to protect itself from large fluctuations in temperature. However, even if the dressed stone slows down the entry of the cold through its inertia, after a certain time it does not become more insulating than a thin wall and thus constitutes a source of wastage. That is why Pouillon added an insulation consisting of a thin wall of terracotta brick in the interior face of the facade with an air gap in the middle.

On the urban scale, the shaded squares and the traditional streets that offer the composition according to the principle of the closed order allows an autonomous protection of the sun during the summer. The arrangement of the buildings around the squares greatly reduces the surfaces exposed to the sunshine in the image of the concept of introversion adopted in the medina.

### **Constructing at a lower cost and in a short time without constraint on economic development**

The third principle of sustainable development is the most important in the architecture of Pouillon. Constructing at a lower cost and in a short time without constraint on economic development was Pouillon's slogan.

The design of the Climat de France differs completely from the different complexes built at the time. Although Pouillon has industrialized the construction of mass housing, he has not followed the same heavy industrialization as in the operations that marked the era. Whereas Pouillon has opted for an industrialization of construction processes by simple element (Barazzetta, 2001). It means industrialize constructive elements such as dressed stone or terracotta brick. The stone constructive system was traditional at the time; Pouillon had to develop a new constructive wall system with dressed stone as building material to gain in construction time, cost and architectural quality.

This constructive system is very economical in time and cost, but it is possible only because the walls are bearers. If we want to describe; it is a floor composed of 14cm of marmite<sup>2</sup>; which is a prefabricated slabs, hollow but closed square that pose upside down on the closed and smooth face to constitute a finite lost formwork (figure 4). Marmites are placed against each other to form a grid like a chocolate bar. The reinforcing bars are placed in the gaps between marmites in both directions of the grid, and there will be which is called a floor with crossed ribs. After the concrete will be poured into the ribs to fill the void between marmites and constituting thereafter joists. The first rows of bricks will be laid before pouring the compression screed to use the grid as a reference frame for walls of the internal partition. (Sayen, 2014)

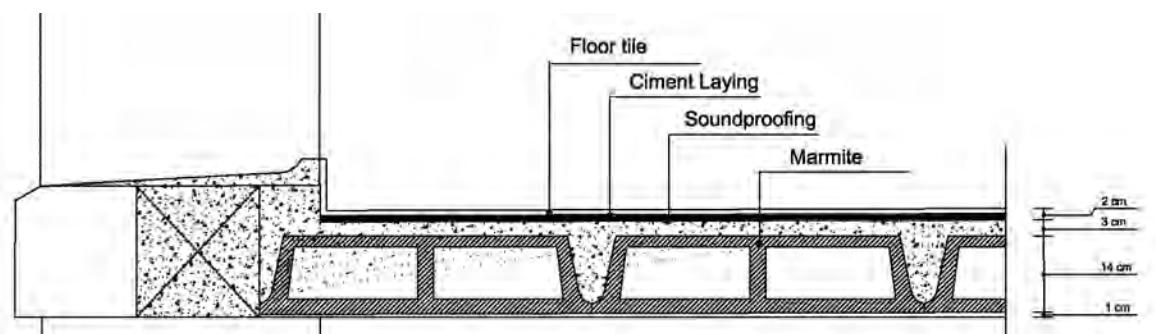


Figure 4: The constructive system of Pouillon

Source : by the author

It should be noted that in the late 1970s, heavy prefabrication was replaced by a policy aimed at developing the use of 'component' in construction. A component was defined as an element of the building manufactured in a workshop independently of a particular project and integrated into the structure without having to undergo shaping on the site (Chemillier, 2002). This is the same principle of industrialization of construction processes by simple element that Pouillon followed in the 50s, which proves once again that his answers were ahead of his time.

<sup>2</sup> A *marmite* is a hollow square, part of the floor structure invented by Pouillon made of staff (a mixture of plaster and fiber) or cement, through which a steel frame and concrete pass, like ribs, to support the floor.

## Conclusion

After this brief passage on the architecture of the 1950s and the vision of Pouillon on the future of housing construction, we have seen that the notion of sustainable development in the 1990s was a reaction against the repercussions of heavy industrialization on architectural quality and the environment. Moreover, even if this way of industrialization in the image of the automotive industry solved the problem of quantity, it had negative repercussions on the architectural quality of the construction and on its environmental impact. In order to maximize its industrialization, the building was considered as an industrial product rather than an architectural object. Despite all this, we have never managed to industrialize the building in 100%. Moreover, the good results that were achieved in the 1950s and 1960s were in artificial conditions favoured by the strong commitment of the state (Chemillier, 2002). Pouillon had another vision of the future of massive housing construction; he opted for an industrialization of construction processes by simple element considering the building as an architectural object more than industrial product. Instead of making a clean sweep of the architecture of the ancestors, he took the best of the traditional cities architecture of 17th and 18th century and updating it according to the technological means of the time. The principles of sustainable development were present in his architecture even before the existence of the report "Our Common Future". This is because the architecture before its heavy industrialization was sustainable and ecological. We needed only to update its construction processes according to the new technological means with keeping in mind that the building is an architectural object and can never be an industrial product like the automotive.

## References

- Barazzetta, G. (2001). *Exigence de la construction*. in J. L. Bonillo (Ed.), *Fernand Pouillon architecte méditerranéen*. Marseille : Imbernon.
- Brundtland, G. H. (1991). *Our Common future*. in Tolba, M.K., & Biswas, A.K. (Ed.). *Earth and Us: Population – Resources – Environment – Development*. (pp. 29-31) United Kingdom: Butterworth-Heinemann.
- Chemillier, P. (2002, June). *L'époque de l'industrialisation du bâtiment après la guerre 1939-1945*. Comité d'histoire du ministère, France.
- Caruso, A., & Thomas, H. (2014). *The Stones of Fernand Pouillon, an alternative modernism in French architecture*. Zurich: gta Verlag.
- Dehan, P. (2009). *La qualité architecturale entre art et usage*, dans « qualité architecturale acteur et enjeux. In Biau, V., & Lautier, F. (Eds), *Processus d'engendrement de la qualité et négociations entre acteurs de l'architecture*. (pp. 88-94). Paris : Ramau.
- Gann, D. M., Salter, A. J., & Whyte, K. (2003). *Design Quality Indicators as a tool for Thinking*. Building Research & Information, 31(5), 318–333. [doi.org/10.1080/0961321032000107564](https://doi.org/10.1080/0961321032000107564).
- Kibert, J. C., (2016). *Sustainable construction: Green building design and delivery*. United Kingdom: John Wiley & Sons.
- Le Corbusier, J. P. (1994), Précision sur un état présent de l'architecture et de l'urbanisme 1930. (p123). Paris : G. Crès et Cie.
- Lucan, J. (1997). *Fernand Pouillon architecte*. Paris : Arsenal.
- Pouillon, F. (1968). *Mémoire d'un architecte*. Paris : Seuil.
- Sayen, C. (2014). *L'Architecture par Fernand Pouillon* ». Toulouse : Transversales.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## From lightweight pioneering steel houses to zero energy buildings

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**Abstract:** In XX Century California, three generations of architects pushed the boundaries of language, experimenting the use of then uncommon materials to build lightweight, modern houses. It all began with Neutra in the 30's, who achieved the ideal of the house made like a car, building his Lovell house out of steel framing and sprayed concrete at a time when his European counterparts applied machine aesthetic to houses who still were brick and mortar below the clean coat of white plaster. Architects such as Ellwood, Eames, Soriano and Koenig produced a fascinating skin and bone aesthetic, making no nonsense use of commercial steel sections in order to produce economical yet refined buildings. However, it was not just their fascinating aspect, but the logical, almost scientific, approach that makes those buildings so appealing. Today's knowledge of materials, energy conservations and building dynamics can produce high performance buildings that greatly improve on yesterday's standard. A case study shows how sites and building technologies work together. Sites was studied to minimize excavations and exploit prevailing breezes in order to minimize use of HVAC. A dynamic analysis of the building was run to determine the composition of walls and roof and glazed surfaces.

**Keywords:** residential architecture, bioclimatic design, dry-assemble technology, nZEB, Californian architecture

### Lightweight Californian steel houses

#### ***Innovation in the twenties***

In his History of Architecture of 1899, Auguste Choisy wrote that "styles do not change following the whimsies of fashion, variations are the results of changes in the construction process". In the early twentieth century, the industrialization of processes in most spheres of man made products, led progressive architects to promote a new wave of industrialized buildings. "If houses were built industrially –wrote Le Corbusier in 1920- in line, as automobile frames, we would quickly see the rise of unexpected, yet healthy, forms, and the aesthetic would be formulated with surprising precision". On the same page we find Richard Neutra, who preached that "the house of the future will be built out of standard steel components, assembled like a car, and it will take on a beauty which will not be based on the old decorative forms, but on a new beauty of rhythm and order" (Neutra, 1931).

However, if Europe was the one pushing the ideal of the "house built like a car", it was America who made this dream possible. Between 1927 and 1929, at a time when his colleagues back home were applying machine aesthetic to houses which were still brick and mortar below the clean coat of white plaster, Neutra was building the Lovell House out of steel and sprayed concrete (fig. 1).

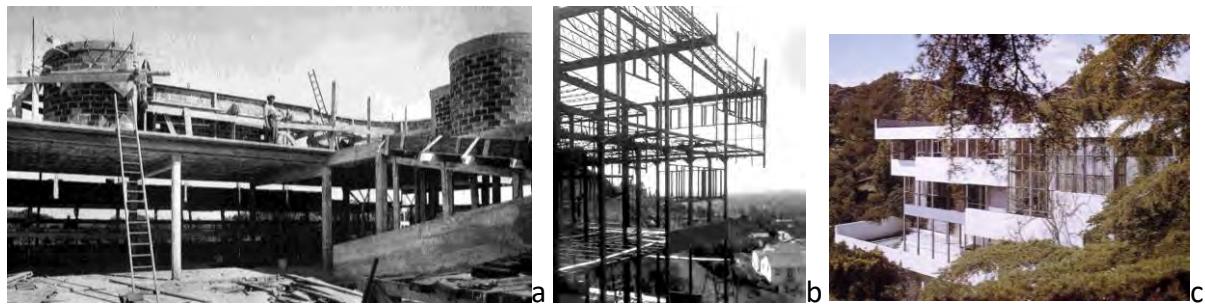


Figure 1 a/b/c. (a) Le Corbusier-Jeanneret, Ville Savoye, 1928-31. (b) (c) Neutra, Lovell House, 1927-29

Neutra's biographer Thomas Hines claims it to be "the first steel framed residence in America". This is a well-established notion, but it is not true. In fact, a research published in 1930 by the America Institute of Steel Construction<sup>1</sup>, records six steel framed homes in 1927, 42 in 1928 and 65 in 1929. In fact, although the first steel framed residence in America was built near New York almost thirty years earlier, what makes the Lovell House stand out and steal the limelight is well summarized by Kenneth Frampton, who defines it the apotheosis of International Style, thanks to an architectural expression directly derived from a steel frame, clad by a light synthetic skin (Frampton, 1980). Design of Steel Buildings by Harold D. Hauf, first published in 1932 and probably the first manual on steel construction in the US, is a good meter of the Lovell House achievement. In fact, studying this manual, it becomes clear that technological and aesthetical innovation did not go hand in hand: besides the framing, the steel buildings were not different from most current production.

### ***Developing a language***

To develop a language that fully exploits the potential of new materials and technologies takes time. If the Lovell House, with its steep site, free flowing plan and big glazed surfaces was making full advantage of steel, it was not yet the epitome of the light steel and glass pavilions associated with California lifestyle. This is mostly due to one reason: steel profiles were not visible in the finished building if not as window mullions (fig. 1b and 1c).

The minimal skin and bone aesthetic, defined by Reyner Banham "The Style that Nearly...", was to appear another thirty years later, at the peak of Arts and Architecture Magazine Case Study Houses program (Banham, 1971). It was the development of a process of expression of the steel frame which allowed Raphael Soriano to show most of it in the forties, and Pierre Koenig to show it all in the fifties. In between these experiences are those of Charles Eames and Craig Ellwood. Eames built for himself a house which was of great consequence, especially in Europe, where it came to epitomize the potential of a residential architecture made out of off-the-shelf components, dry assembled (fig. 2b). Ellwood built some significant specimens which helped define the new architecture vocabulary, before shifting towards Miesian mannerism.

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<sup>1</sup> Facts and Figures about Steel Construction

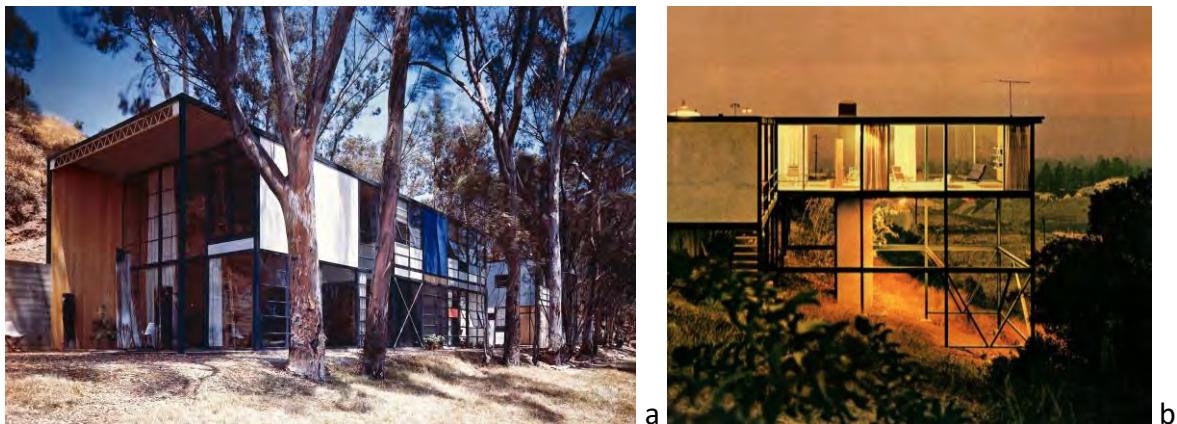


Figure 2 a/b. (a) Charles Eames, Eames House, 1949 (J. Shulman/C© J. Paul Getty Trust). (b) Craig Ellwood, Smith House, 1958 (© Marvin Rand)

Whilst Soriano tested the use of steel in houses more than anyone else before him, proving it was possible to use the material within ordinary budgets, it was Koenig who delivered the most memorable shot in the CSH #22, hovering above West Hollywood and incarnating modern lifestyle in countless movies and commercials (fig. 3a and 3b).



Figure 3 a/b/c. (a) Raphael Soriano, CSH #1950 (J. Shulman/C© J. Paul Getty Trust). (b) Pierre Koenig, Case Study House #22, 1959-60 (J. Shulman/C© J. Paul Getty Trust). (c) P. Koenig, Case Study House #21, 1958 (©author).

Still, Koenig did not limit himself to fully developing a convincing aesthetic for steel in residential buildings, but moved one step further in pioneering the use of passive means to cool his houses at a time when steel and glass buildings were made possible not only by the materials themselves, but by the massive use of HVAC systems. The fact that these passive means became so inextricably tied to what makes the best Koenig's buildings iconic is proof of how the conscious use of energy and available resources can the final look of a building in a successful way. In CSH #21, his most successful demonstration of a repeatable building for mass production, he relied on the orientation of the building to block the sun, completely blinding facades on the East and West, where solar radiation is more difficult to control, and using a vertical external sunscreen on the South and North facades (fig. 3c). He adopted wide overhangs in CSH#22, which worked especially well in giving the house a "floating" quality over the dramatic hillside site.

### ***Moving forward***

Although fascinating on their own, buildings by Soriano and Koenig share a logical, almost scientific, approach that makes them especially appealing. Each is a step forward in pushing the progress of a specific building type. Whilst Soriano devoted over 20 years of his professional life to releasing the potential of steel, in his later years he applied himself to exploring the application of the even lighter aluminum, while Koenig moved forward on the

path of exploiting passive means of getting rid of HVAC, establishing the Natural Forces Laboratory at USC. The interest in bioclimatic design already present in his work of the fifties was further developed in projects such as the house he built for himself in the mid-eighties, where free cooling techniques were tested.

The first Californian experiences of bioclimatic and low-energy houses of the 60s and 70s were joined by the “intelligent building” concept of the 80s, when several buildings gradually included the control of various equipment and systems. From these experiences, the US Department of Energy (DOE) launched the Zero Energy Home Initiative (ZEH) in 2003 and the Building Technologies Program (BTP) in 2008 (Panagiotidou and Fuller, 2013). For the ZEH, five demonstration projects have been developed, most located in California. For the BTP, the aim is to introduce a common national Zero Energy Building definition with supporting nomenclature and guidelines to facilitate its use. Crawley et al. (2009) has provided the first definition of ZEB as “a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies”. A broadly accepted definition of ZEB metrics and boundaries is foundational to efforts by governments, utilities, or private entities to recognize or incentivize zero energy buildings, and would have a significant impact on the development of design strategies for buildings<sup>2</sup>. Then, the net Zero Energy Building is not a building where the energy demand is zero, but a building for whom the energy delivered is equal to the exported energy for 1 year of operating.

### **The Case Study: the Grand View drive House GVH**

Lessons from the former generations along with new building design technology aids were applied to the design of a new single family residence in the Laurel Canyon area of Los Angeles in 2013<sup>3</sup>. Here, the constraints posed by site, accessibility and building codes made for a small project of amazing complexity, located in a high fire hazard severity zone in a region whose seismic risk ranks among the highest in the world. The lot is steep and narrow, sloping South to North on top of the ridge of the hill above West Hollywood. It is an interesting coincidence that the site at 8413 Grand View Drive sits on an ideal line joining Case Study House #21 and #22 by Pierre Koenig.

The themes developed in those seminal houses overlap in Grand View: the site shape calls for a building orientated on the North/South axis as in CSH#21, and the challenge of building on a slope, dramatized in CSH#22, is even more demanding here. Yet, the steep slope and the height limit regulation implies that a single story pavilion as the CSHs is out of question, thus linking Gran View House GVH to other precedents in the off the shelf prefabricated steel framed houses lineage: Helmut Schulitz’s own house in nearby Beverly Hills and Koenig’s Gantert House in the Hollywood Hills (fig. 4). Dimitry Vergun, structural engineer for the latter and Grand View House, is an even more direct connection ring.

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<sup>2</sup> <https://energy.gov/eere/buildings/zero-energy-buildings>

<sup>3</sup> Gran View House, Los Angeles (USA). (PAT. architects, 2013)

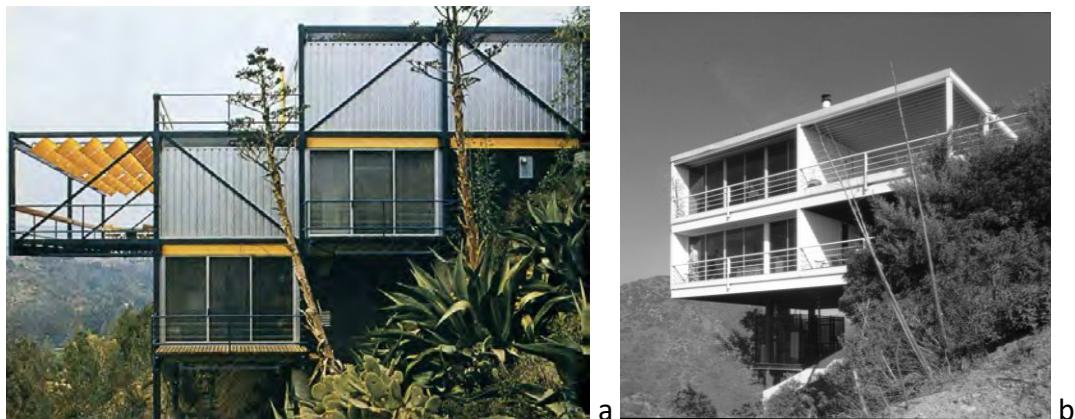


Figure 4 a/b. (a) Helmut Schulitz, Schulitz House, 1976. (b) Pierre Koenig, Gantert House, 1981 (J. Shulman/© J. Paul Getty Trust).

From the road the lot slopes downhill facing the Canyon. Early studies explored the potential of the building to grow in height trying to reach city views versus the temptation to cantilever a simple box on the size of the hill, minimizing excavations. The final massing is composed by a three storey “tower” and a two storey “box” separated by a pool. The garage at street level is on top of the tower, a studio/recreation room is at level -1, a storage at -2, which is the level the “box”, partially cantilevered, is accessed. Served and servant spaces are separated and clearly articulated. Not only service spaces such as storage and garage are separated by the living quarters, but also vertical circulation and toilets are moved to the periphery of the building and become both a mean for architectural expression and a way to fit the trapezoidal contour of the lot.



Figure 5. PAT. architects, Grand View House, 2013 (@patdesign.it).

### ***Integrated design: architecture, technology, structure and systems***

An integrated design team was assembled for the task and worked with an holistic approach to nurture synergies and interactions. The case study shows how site and building technologies worked together to improve building efficiency. The Site was studied to minimize excavations and exploit prevailing breezes in order to minimize use of HVAC. The building was oriented on the North-South axis, with sides facing East and West almost completely blinded in order to control solar radiation, while North and South facades, easier to shade, are glazed and open to cooling breezes. Lightweight, dry assembled techniques, typical of the Region and appropriate for the task of building on a hillside, were preferred. Nevertheless, it was deemed appropriate to have some mass for thermal comfort. The use of PCMs, summing up lightness and passive cooling properties, was explored and eventually

discarded. Steel bays spanning 26 feet support composite metal floors, whose screed is polished and exposed in order to avoid further finishing and exploit the thermal mass. A dynamic analysis of the building provided the basis for determining the composition of walls and the roof and the specs for glazed surfaces. The analysis led to discard the use of SIPS panels, originally envisioned for their ease of construction, LEED credential and high R value, and opt instead for a multi layered ventilated facade clad in galvalume sheets.

All the design strategies contribute both to reduce the energy needs enhancing energy efficiency with passive and active technologies, and to generate on-site energy balancing cost and benefit. In term of ZEB strategy, table 1 summarized the measures applied in the case study presented.

*Table 2 – net Zero Energy Building strategies of the Grand View drive house*

ENERGY EFFICIENCY	DESIGN STRATEGIES
site and orientation	Orientation on the North-South axis, with sides facing East and West almost completely blind in order to control solar radiation.
advanced thermal insulation	Dry assembled envelope highly insulated and without thermal bridges.
high thermal mass	Dry assembled envelope with high density insulations and exposed screed to exploit the thermal mass.
sun-shading and ventilation	Glazed North and South facades, shaded by the balconies and overhangs, opened to cooling breezes and natural light.
mechanical ventilation	Efficient HVAC system embedded in ceilings and walls and integrated with passive night cooling. It takes benefit from the building thermal mass.
comfort outdoor	The presence of the pool cools the air on the outdoor spaces
water demand	System for collecting and reusing grey and rain water
ON-SITE ENERGY PRODUCTION	
solar thermal collectors	Domestic hot water production
photovoltaic panels	Electricity for systems, lighting and home's appliances

### ***Dynamic analysis***

A dynamic analysis of the building under study has been carried out in order to determine both the composition of its walls and roof and the thermal specs of its glazed surfaces. A dynamic analysis requires little extra effort at the design stage and bring advantages such as: the optimization of the envelope system and its relationship with the mechanical systems, reducing operational energy loads; it allows to earn extra points in voluntary environmental assessment tools and the related economic benefits.

From its early stages the design of a nZEB building requires an integrated approach involving different professionals and a careful evaluation of the thermal flows needed to determine the overall building energy balance. The design is aimed at assessing and controlling the future winter and summer thermal performances reducing the load on air-conditioning plant systems and ensuring high hygrothermal comfort.

The design choices of Grand View Residence were all supported by thermal analysis derived from simulation models and characterized by different detail levels on the basis of the specific project needs and phases. For each component of the building envelope, both winter and summer thermal behaviour parameters were compared with the project targets so as to validate or reject the choice made for stratigraphies and constructive nodes. Table 2 allows us to compare the values of thermal transmittance (U), periodic thermal transmittance (Y), phase shift ( $\phi$ ) and attenuation (a) of specified building roofs (R) and walls (W) with the target values assumed by the designers. The building components adjoining the external environment and exposed to sunlight, are characterized by high thermal lag values: more than 7 hours for walls and more than 12 hours for horizontal roofs

being particularly affected by solar radiation in the summer and therefore potentially responsible for the interior overheating. The choice of using insulating materials characterized by a low value of thermal conductivity, high values of mass density and specific heat, enables a lightweight dry assembled structure to get high summer thermal performances.

*Table 2 - Performance characteristics of the individual components.*

	U [W/(m <sup>2</sup> K)]	U <sub>target</sub> [W/(m <sup>2</sup> K)]	Y [W/(m <sup>2</sup> K)]	¶ [h]	¶ <sub>target</sub> [h]	a [ - ]	ENVIRONMENT
W01	0,225	< 0,4	0,082	7h 01'	> 7 h	0,3637	SUN
W02	0,223		0,062	7h 54'	> 7 h	0,2808	SUN
W03	0,388		-	-	-	-	GROUND
R01	0,386		0,235	5h 01'	-	0,6098	SHADE
R02	0,365		-	-	-	-	GROUND
R03	0,182		0,046	12h 19'	> 12 h	0,2539	SUN
R04	0,190		0,047	12h 58'	> 12 h	0,2482	SUN
R06	0,183		0,023	7h 59'	-	0,1233	SHADE

The design choices with regards to the shape, orientation, and the exposure of the building, as well as the envelope technologies and facilities, were supported by an hourly thermal evaluation (dynamic analysis), through the use of TRNSYS software - Transient System Simulation Tool. The calculation has been carried out for a full calendar year in order to quantify both winter and summer thermal loads, temperature profiles in the absence of air conditioning and air conditioning operating hours to maintain comfort levels. Table 3 shows the boundary conditions used for the TRNSYS computation.

*Table 3 - Boundary conditions used for the computation*

Parameter	Values
Temperature	20°C heating 26°C cooling
Local employment / operating systems	24/24h, 365 days
Internal thermal contribution	5 W/m <sup>2</sup> (50% convective, 50% radiative);
Ventilation	0,5 vol/h

Figure 5 illustrates the results of the simulation analysis of two types of insulated and low-emissivity glass: A)  $U_g = 1,4 \text{ W}/(\text{m}^2\text{K})$  and  $g = 0,59$ ; B)  $U_g = 1,26 \text{ W}/(\text{m}^2\text{K})$  e  $g = 0,4$ . The choice of glass B) allows to reduce solar radiant contribution: as a consequence air conditioning load is reduced by 33% in the summer, thermal requirement is reduced by 36% in the summer even though, in the meantime, it is increased by 16% in the winter.

The building as a whole, has a thermal requirement of:

- Summer: 20,98 kWh/(m<sup>2</sup>year)
- Winter: 18,33 kWh/(m<sup>2</sup>year)

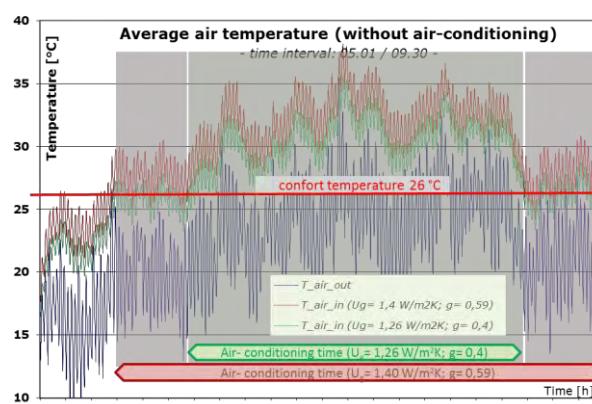


Figure 5. Dynamic simulation analysis of two types of insulated and low-emissivity glass: A)  $U_g = 1,4 \text{ W}/(\text{m}^2\text{K})$  and  $g = 0,59$ ; B)  $U_g = 1,26 \text{ W}/(\text{m}^2\text{K})$  e  $g = 0,4$

## Conclusion

Following in the footsteps of Auguste Choisy, Raphael Soriano said that “the process of questioning, validating, and designing for performance is what bring progress in architecture” (Laskey, 1988). New aesthetics can arise as a result. Advances in construction techniques and computer aided design, along with a rising conscience of the centrality of an integrated design approach can foster both efficiency and the development of an architectural language. But aesthetics by itself does not tell the whole story.

Looking at picture 6, a comparison between the stratigraphy of CSH#21 and GVH highlights how the complexity has increased below the skin of buildings.

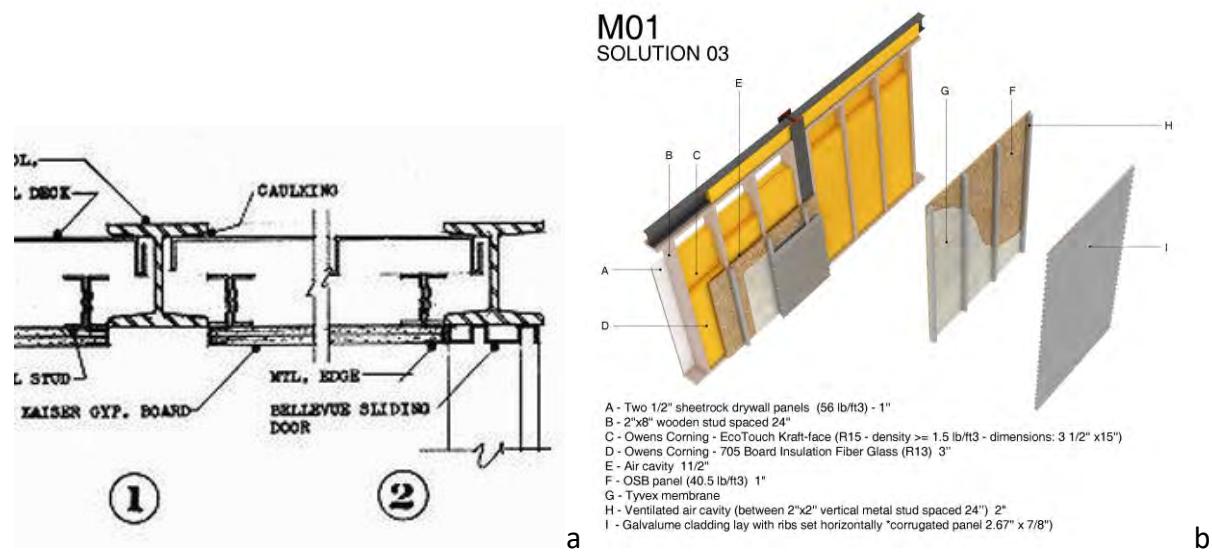


Figure 6 a/b. (a) Koenig, CSH#21, 1958 (b) PAT. architects, Grand View House, 2013 (©patdesign.it).

New software allow to verify design hypothesis, guiding choices toward maximum performance and improving the understanding of the building over its entire life cycle. An interesting outlook of the research could be the comparison of several recent buildings of the same typology in order to recognize benchmarks and improve the state of the art.

## References

- Choisy, A. (1899). *Histoire de l'Architecture*, Gauthier-Villars, Paris.
- Le Corbusier (1923). *Vers une Architecture*, Edition Crès, Paris.
- Neutra R.J. (1931). Houses at \$ 150, in *Detroit News*, 1/3/1931.
- Hauf H.D. (1932). *Design of Steel Buildings*, J. Wiley & Sons, NY.
- Frampton K. (1980). *Modern Architecture: a Critical History*, Oxford University Press, NY.
- Banham R. (1971). *Los Angeles: the Architecture of Four Ecologies*. Allen Lane, London.
- Panagiotidou M., Fuller R.J. (2013). Progress in ZEBs – A review of definitions, policies and construction activity. *Energy policy*. 62, 196-206
- Crawley D., Pless S., Torcellini P. (2009). Getting to net zero, *ASHRAE Journal*. 51 (9) 18–25.
- Musall E., Weiss T., Lenoir A., Voss K., Garde F., Donn M. (2010), Net Zero Energy Solar Buildings: An Overview and Analysis on Worldwide Building Projects, in: EuroSun Conference 2010, Graz, Austria
- Hines T. (1982). *Richard Neutra and the Search for Modern Architecture*, Oxford University Press, NY.
- Laskey M. (1988). *Substance and function in architecture*, Oral History Program, UC Los Angeles.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Outsider ethics and marginalized aesthetics: The value of contemporary environmental philosophies for designing sustainable architecture

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**Abstract:** In this paper, I will explore the work of two contemporary environmental philosophers: Gernot Böhme, celebrated for his philosophy of architectural atmosphere although less known for his work on ecological aesthetics, and Luce Irigaray, a French philosopher renowned for her work inspiring a generation of feminist scholars but less well discussed for her work on environmental ethics. For Böhme, our designed environments are experienced through atmosphere; we feel our own presence in a built environment and feel the environment in which we are present. His approach to design depends on feeling experienced through being in space rather than seeing space or imagining it. Irigaray, on the other hand, now in her eighties, distinguishes experience as different between the sexes, not as already cultural, but rather to be cultivated. Her philosophy is provocative and challenged by many; while on the margins of Parisian intellectual society, she still works, teaches, and writes prolifically about environmental ethics. This paper examines how these two marginalized ecological philosophers can benefit the field of environmental design.

**Keywords:** philosophy, ethics, aesthetics, environment, architecture

### Introduction

What relevance has mood or atmosphere to the discourse of sustainable design? What is the perceived importance of feeling to an architecture that can engage and communicate with users the problems of sustainable development? These questions are seldom raised in the discourses associated with green and sustainable architecture, but feeling connects us with our environment and while the science of climate change produces statistics distancing the problem, and the workings of an environmentally sustainable building can remain obscure to many, feeling is immediate, physical, every day; it is about how we experience our environment in the moment.

According to Gernot Böhme, a contemporary German philosopher, our designed environments are experienced through feeling; we feel our own presence in space and feel the space in which we are present. He establishes an approach to understanding architecture that he describes as an aesthetic dependent on feeling, experienced through being in space rather than seeing or imagining it. Similarly, in his eco-aesthetics, we feel our relation to nature: We feel nature's crisis because we feel the nature we are ourselves.

Luce Irigaray, on the other hand, is an influential feminist philosopher whose work has been pivotal to feminist thinking, shaping a generation of feminist theorists. Liberation is to be experienced, she argues, with our bodies and intimate feelings, in our environments, in place. Irigaray's philosophy is radical and provocative and challenged by many. While on the margins of Parisian intellectual society, with her works refused in her native language, and

challenged by those seeking liberation in post-human identities (I describe her philosophy as post-post-human), she teaches and writes prolifically about sexual politics and environmental ethics.

The intention of this paper is thus to examine how in the context of environmental concerns social aspiration is limited, in particular in the literature on sustainable development. The aim is to address the question of design's role in the engagement and communication of environment awareness through feeling and to carefully and critically examine texts of Böhme and Irigaray to evaluate how these rich relational and ecological philosophies, engaging with ethics and aesthetics, mood or feeling, can supplement the discourse of sustainable development to benefit the field of sustainable design.

### **Sustainable development and social aspiration**

Sustainability can be explained in many ways, but sustainable architecture is focused on how we live. It can be ethical and aspirational. It can ask us how we can live in ethical relationships with other living beings without excessively exploiting our shared environment, but this is most typically expressed as a concern for assessing performance. While sustainability is a social construct, meaning different things to different people across cultures and locations, it is also an environmentally sensitive and responsible expression of our relationship to other living and non-living things. Sustainable design is about our social relationships as well as our relationships to nature and, moreover, it is about how we would like them to be.

In 2013, the United Nations (UN) created the Sustainable Development Goals, replacing the previous Millennium Development Goals, as a definitive statement on aspiration for human development. The Sustainable Development Goals (SDGs) (United Nations, 2015) are a set of 17 global goals with 169 targets among them, including ending poverty in all forms everywhere, ending hunger, ensuring healthy lives for all at all ages, and ensuring inclusive and equitable education. The goals address gender inequality, and goal 5, in particular, states: "Achieve gender equality and empower all women and girls" (see Table 1; United Nations, 2015). Other goals concern access to energy, water, productive employment, resilient infrastructure, and safe cities, addressing climate change and environmental degradation, and promoting sustainable consumption and peaceful society. These SDGs are ambitious, and they supersede the eight Millennium Development Goals (MDGs). Furthermore, the *2030 Agenda for Sustainable Development* asks world leaders to begin efforts now to achieve the SDGs by 2030.

Initiated by Ban Ki-moon, the SDGs are a shared vision for humanity and a social contract between the world's leaders and the people; they constitute a to-do list for people and planet. They include 17 goals to transform our world for the better. However, there are criticisms, and the very number of goals and targets has been called into question. The degree of accountability of all the parties who have voluntarily adopted the agenda is vague and like the scientists' statistics for climate change they are distant goals. The SDGs represent a common aspiration as a policy tool.

Table 1. Sustainable Development Goals (from United Nations, 2015)

Goal 1	End poverty in all its forms everywhere
Goal 2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3	Ensure healthy lives and promote well-being for all at all ages
Goal 4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5	Achieve gender equality and empower all women and girls
Goal 6	Ensure availability and sustainable management of water and sanitation for all
Goal 7	Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
Goal 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 10	Reduce inequality within and among countries
Goal 11	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12	Ensure sustainable consumption and production patterns
Goal 13	Take urgent action to combat climate change and its impacts
Goal 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

### **Feeling, ethics, and sustainable design**

So, if architecture as a discipline invites engagement and inhabitation, how can architects and designers invite users to engage with the problem of sustainable development? Architectural aesthetics is a discourse positioned somewhat at odds with the performance agenda of sustainable design, including that it might have some of the same distant social and humanitarian aspirations as the SDGs. However, researchers recognize diverse ways of constructing knowledge, even in the field of construction, and, moreover, within the field of construction research, scholars are increasingly challenging methods adopted to collect performance data, questioning tools and measures, and highlighting the complexity of the impact of any building on its environment, including its social and economic contexts. Nevertheless, these are experimental studies with little impact as yet on the industry and professions. Such studies are themselves aspirational. Confronting accounting perspectives that promise to build future ecological worlds is a difficult challenge in light of biases of the architectural and construction professions.

So, what is design's role in engaging and communicating the problem of sustainable development? Also, can eco-aesthetics be separated from architectural ethics? What is really at stake with such questions?

We feel nature and we feel its destruction. We feel it as the nature we are ourselves. This is Böhme's argument. So, we might be able to feel, and feel intimately, our own impact on the environment. We can thereby act ethically toward the nature that we are ourselves. We can better feel our lived environment, we can feel ourselves in our environments, feel the reality of our existence in relation to our environments and, in this way, cultivate a more

intimate ethic toward the environment. This is a powerful perspective as a way of engaging people with the problem of environmental crises and motivating action. As designers working in the built environment, the important addition to sustainable design becomes one of communication.

This sort of dialogue, this understanding of our own nature in relation to nature, Böhme has described as an eco-aesthetic discourse (*ökologische Naturästhetik*). According to Böhme, nature must be recognized as our partner and we should gradually adapt to such a partner relationship. Nature is not something we have left in our becoming civilized; nature and the natural in us are not to be overcome. As he argues, "...it is only now that we realize that what has been carried out as the domination of nature is, in fact, a totally impossible project" (Wang, 2014).

Nevertheless, Irigaray is of a similar age to Böhme and she is known for her work on sexual difference, or rather her ethics of sexual difference, that which she calls *sexuate* difference. Her philosophy is not without some contestation, and she similarly describes starting with the nature we are ourselves, returning to ourselves, discovering a natural belonging, but importantly for Irigaray this is also *sexuate* belonging: It is the discovering of the life that we are ourselves in relation to *sexuate* difference rather than in our cultural descriptions and designations (Irigaray, 2015, 101). It is a rethinking of relations from intimate relations and this means rediscovering a living embodiment in ways not yet culturally recognized. Like Böhme, she argues that "...the first ecological gesture is to live and situate ourselves as living beings among other living beings in an environment that allows life to exist and develop" (Irigaray, 2015, 101). So, she adds to an eco-aesthetic a perspective difference in feeling between the sexes, an 'ethic' to be culturally recognized.

Hence, if we feel nature, as Böhme suggests, we feel our relation with the natural environment, we feel ourselves as nature; Irigaray asks, do man and woman feel in the same way, and can we engage with such questions without falling into stereotypes? Moreover, is this a development of an ethic that can cultivate the emergence of at least two equal and different subjectivities? We can reflect on our social experience, our relationships and our sensory experience, and we can find excitement in the post-human and futuristic; many different perspectives engage and incite. The document that describes the United Nations Sustainable Development Goals is, after all, entitled *Transforming Our World: The 2030 Agenda for Sustainable Development*. However, entering the world of these philosophers is not the same work as developing the SDGs. So, why bring tricky outsider ethics and marginalized aesthetics into the field of sustainable architectural design? The value is one of criticism, but the validity of such criticism is immediately at risk because of its outsider status. This is an argument about feeling, every day, immediate, physically embodied; however, the merit of such is yet to enter into the dialogue on sustainable design.

In her most recent publication *To Be Born* (2017), Irigaray writes, "Who could maintain, that he or she is not in search of their origin in their dreams regarding the future, their amorous desires, their aspirations for the beyond? ... who is able not to make up one's mind according to a secret nostalgia for at least understanding in what one's origin consists?" (Irigaray, 2017, 3). These feelings are understood through cultural traditions, through language, poetry, art, often lamenting the loss of a truly natural environment, but the feelings seduce, romance us, and are artificial. Our reality is, as Irigaray argues, that we are made not from one apparent source of such nostalgia, to which we long to return, for refuge, for peace, a desire characteristic of so much of environmental philosophy, but our

existence is "...an actualization of the elusive event of a meeting between two humans" (Irigaray, 2017, 4). Feeling is key to Irigaray's philosophy, and feeling is how we can rethink environmental awareness. However, this is the ecological reality of an as yet to be recognized and cultivated relationship between at least two human subjects in a relationship of equality and difference. She writes:

*...so as long as we do not consider the two ec-stasies from which we can exist as humans: the ec-stasis with regard to our origin, and the ec-stasis for which our desire calls us. These two different ec-stasies, in a way these two not being must be taken on in order that we can discover what means our 'to be' as human and endeavour to incarnate our own destiny* (Irigaray, 2017).

So, we need to question our reality and discover our own ecological and sexuate belonging; this is a radical perspective, albeit one that also critically situates body and feeling, mood and feeling, in questions of environmental and sustainable design. Outsider ethics and marginalized aesthetics have some value, not only to serve as a critical lens but also to enrich the discourse of sustainable architecture through the reevaluation of feeling.

### **Outsider Ethics and Marginalized Aesthetics in Sustainable Design**

We design buildings to be energy efficient and to be ethical. We design them to be beautiful, and yet we tend not to ask people how in actuality they feel in buildings or how they understand their built environments. We do not fully recognize the power of the sensory dimension in our methods, in our predictive energy modeling tools that shape how we understand design, or in how we assess buildings and their performance in actuality. With the few exceptions of theorists who are described as engaged with humanities perspectives on climate change (Hume, 2011, 2015; Barnes et al., 2003; Ingold, 2011), architects and scholars following research methods that challenge dominant intellectual or policy research perspectives (Divine-Wright, 2005) and researchers examining and adopting innovative methodologies in construction science (Pink et al., 2010), the dominant perspective from which we view the problem of environmental design and, moreover, sustainable design in architecture is that of the sciences.

The need to widen our perspective on research methods is, nevertheless, being explored in building and construction research. Pink et al. (2010), for example, describe their work as a response to a more thorough application of social science theory and methodology to industry research. They argue that approaches to research can even be designed to enable sensory ethnographers to share other people's experiences and "...to generate closer and empathetic understandings of these experiences" (Pink, 2010). However, there is still some need to step back and engage with philosophers and philosophies, and with humanities perspectives, that are driving such motivations. The call to re-envision a human future and ecology is radical and, as Irigaray writes, "... it would be advisable to wonder about what being alive signifies, and whether we are really living, or how we could be or become living" (Irigaray, 2015, 101).

Furthermore, while social theories of behavior change are developing and Gill et al. (2010) argue the field is a major untapped route for energy savings, the varying knowledge, attitudes, and abilities of users or occupants nevertheless present a fundamental barrier to strategies of education and building performance optimization. Building researchers tend to conceive the problem of sustainable design as a technical challenge to which acceptance needs to be solicited. Moreover, future strategies to educate users require, they argue, "...a

thorough interdisciplinary understanding of attitudes and behaviours due to their inherent complexity and impacts" (Gill et al., 2010, p. x). Behavior, of course, is a person's response as a consequence of complex interactions between internal and external factors, which for all intents and purposes, describes how affect, the vague feeling of being in a building, motivates action. These factors, they argue, might include "... emotional, moral, habitual, contextual, attitudinal, social, normative, and control factors" (Gill et al., 2010, 496). There are methodological questions to be directed to the field, but while the question of feeling is raised in performance-based studies of energy-efficient and sustainable design, the question of feeling is not addressed *as* feeling. Feeling in terms of an emotional connection to place, however, is not new to architecture (Seamon, 2000; Manzo, 2003). It is just that the fields are disconnected and Böhme and Irigaray are new philosophers to enter the conversation on environment and place and to offer perspectives on questions of co-existence between us and in relation to the natural environment.

Böhme's eco-aesthetic describes a relationship between the human and nature, but Irigaray questions the very feeling for such an original relationship and indeed the ethics of the feeling. She argues that romantic feelings for nature are artificial and created by cultures, which at their foundation are unethical with respect to the environmental. We might say that her radical philosophy challenges the reality of Böhme's eco-aesthetic, as well as the ethics of his approach. It also challenges the value of environmental philosophies and the traditions to which they belong and questions, radically questions, the human condition. Also, perhaps without articulation, Irigaray's is also contested by both feminist philosophies and those working with the tradition.

## **Discussion**

So, what should we do about feeling, this dimension of experience with competing philosophical perspectives? The dominance of a technical point of view in sustainable building design is shaping a growing alternative conversation, which includes provocative and political philosophies, but design is also emerging as a method by which to address these questions. Why examine this field through the work of these two philosophers – Böhme and Irigaray? Why is this sort of radical, this sort of outsider, significant? Both seem to address questions of coexistence (of man and nature, man and building, man and woman, man and woman, and nature), together with the felt, bodily or experiential reality of our environmental crises. However, for Böhme, what counts in terms of our environmental crises is that we can rediscover our identity as natural beings "...and develop the consciousness that our body is the nature that we ourselves are" ("Der Leib ist die Natur, die wir selbst sind") (Wang, 2014). He argues that we must recognize that we care about nature because it affects us, it has been affecting us, and it will continue to affect us. He states that "...finding ourselves involved in environmental degradation, it is our own nature that is being affected" (Wang, 2014). What current environmental conditions have destroyed is thus not the object that is the environment, or that of our own nature, but our relationship with it. For Irigaray, the tradition of philosophy, a patriarchal tradition that has excluded socially marginalized voices, including women, does not value questions of embodiment or the rediscovery of embodiment or the reality our ecological co-dependency, the intimacy of our sharing of the world. It is this tradition that has destroyed our relationship to our environment. She writes: "This tradition has, in this way, rendered us extraneous to our environment, extraneous to one another as living beings, and even extraneous to ourselves" (Irigaray, 2015, 101).

Böhme's major works on eco-aesthetics or ecological aesthetics of nature (*Ökologische Naturästhetik*) are largely untranslated, but they include *Für eine ökologische Naturästhetik* (1989), *Atmosphäre: Essays zur neuen Ästhetik* (1995), and *Die Natur vor uns. Naturphilosophie in pragmatischer Hinsicht* (2002). The difference between the co-existence suggested by Böhme and that offered by Irigaray rests in the intimacy with which we experience a natural or ecological belonging. According to Böhme, our interest in nature and in our environmental crises is not motivated by a selfless concern to save the earth, but by a concern for ourselves: It is our own nature being affected. Irigaray, however, calls for a deeper intimacy and an ethics toward the environment by considering social relationships first and discovering a way to recognize the embodied versus sexuate difference.

So, which should be the preference for the field of design, if indeed sustainable development is aspiration? Is Böhme's approach, mediated by an understanding of nature and our human experience, steeped in tradition, the real correspondence with nature, or is Irigaray's the more ethical approach and more attentive to cultural and sexual differences?

Böhme's *ökologische Naturästhetik* is not a visually focused aesthetic view about whether nature is beautiful or not; it is about how nature influences our own feeling of being there, our locatedness (*Befindent*). He argues that it is through our senses that we feel the environment in which we are located and it is the atmosphere of an environment that brings the human situation and the quality of the environment together (Wang, 2014). According to Irigaray, however, we have subjected this world, our world, within ourselves as well as outside ourselves, to a fabrication, an artificiality, one that prevents us from finding ourselves, our locatedness (Irigaray, 2015, 102). While the senses still offer a way to cultivate feelings, our senses are, she writes, "...one of the mediators through which we can pass from a mere natural belonging to a cultured humanity, because they represent a privileged access to our communication with the world and with the other(s)" (Irigaray, 2015, 102). Even to value our embodiment and recognize the value of our sensory experience, we need to co-construct a culture which understands an intimate co-existence: We need an eco-aesthetic of sexuate co-habitation. Environmental and sustainable buildings can be pleasurable to live in, beautiful at a sensory level, and this may be an immediate and physical way to engage with people and communicate the importance of environmental awareness and motivate action. This would be Bohme's argument. However, is this an eco-aesthetic and ethical theory in terms of our own feeling of being there, for both man and woman? Can a more intimate approach appeal more as philosophy that considers the variety of social inequalities in experience and cultural differences, including those of women? Böhme's thinking about architecture and atmosphere suggests an experience through all the senses: a multisensory experience. Architecture is best understood through feeling. Böhme discusses sexual difference as a discovery in relation, but this is not the same sort of intimate discovering or embodiment and relationality that Irigaray describes. Living beings are sexuate, Irigaray argues, and if we continue to consider ourselves as neutered individuals, if we sustain a misrecognition, we cannot behave in an ecological way (Irigaray, 2015, 103).

There is a trail of implications, not the least of which is the failure of sustainable building design in actuality if we continue to disregard the social dimension of sustainable design and how architecture can engage and communicate. Buildings do not use energy, people do; the growth of knowledge about energy use and user behavior in buildings is not leading to better user education. As Janda argues, "...no one is accepting responsibility for

the education of the 99.3% of the population who use buildings" (Janda, 2011, 20). The problem does not simply involve communication, it also involves intimate engagement. Without exploring the significance of complex interactions of building and user, without a reason to include the affective dimension of our environmental experience, and without a theory regarding how such affect shapes our understanding, architects and other building professionals will continue to underestimate its power of feeling to engage and communicate the problems of sustainable development. I have put forward an argument and I want to conclude with the idea that radical thinking is needed; outsider ethics and marginalized aesthetics can provoke the building sciences and can present a critical perspective of value to the conversation on sustainable design. We need critical thinking, not simply for the sake of criticism, but so that we can regain our humanity, our aspirations, our feeling, in these current crises. This is not the end of an argument but only the beginning: To be an environmentalist, to claim oneself to be an environmentalist, before questioning our cultural traditions does not really make sense (Irigaray, 2015, 101). Sustainable architecture needs philosophy as well as science.

## References

- Barnes, J., Dove, M., Lahsen, M., Mathews, A., McElwee, P., McIntosh, R., Moore, F., O'Reilly, J., Orlove, B., Puri, R. and Weiss, H., (2013) Contribution of anthropology to the study of climate change. *Nature Climate Change*, 3(6), pp. 541-544.
- Böhme, G. (1995) *Für eine ökologische Naturästhetik*. Frankfurt am Main: Suhrkamp, Verlag.
- Böhme, G. (1998) *Atmosphäre. Essays zur neuen Ästhetik*. Frankfurt am Main, Suhrkamp, Verlag.
- Devine-Wright, P. (2005) "Beyond NIMBYism: Towards an integrated framework for understanding public perceptions of wind energy." *Wind Energy* 8.2: pp. 125-139.
- Gill, Z. M., Tierney, M. J., Pegg, I. M. and Allan, N. (2010). Low-energy dwellings: The contribution of behaviours to actual performance. *Building Research & Information*, 38(5), pp. 491-508.
- Hulme, M. (2011) "Meet the humanities." *Nature Climate Change* 1.4, p. 177.
- Ingold, T. (2011) "Landscape or Weather World?" In T. Ingold (ed.), *Being Alive: Essays on Movement, Knowledge and Description*. London: Routledge. pp. 126-135.
- Irigaray, L. (2017) *To Be Born*, London: Palgrave.
- Irigaray, L. (2015) "Starting from Ourselves as Living Beings." *Journal of the British Society for Phenomenology* 46(2), pp. 101-108.
- Janda, K. B. (2011) Buildings don't use energy: People do, *Architectural Science Review*, 54:1, 15-22
- Manzo, L. C. (2003) "Beyond house and haven: Toward a revisioning of emotional relationships with places." *Journal of Environmental Psychology* 23: 1, pp. 47-61.
- Pink, S., Tutt, D., Dainty, A. and Gibb, A. (2010) Ethnographic methodologies for construction research: Knowing, practice and interventions. *Building Research & Information*, 38(6), pp.647-659.
- Seamon, D. (2000) "A way of seeing people and place." In *Theoretical perspectives in environment-behavior research*. Springer US, pp. 157-178.
- United Nations (2015) *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations.
- Wang, Z. (2014) "In Interview with Gernot Bohme." *Contemporary Aesthetics* Dec. <http://www.contempaesthetics.org/newvolume/pages/article.php?articleID=713>



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Biomimetics in architecture

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**Abstract:** The purpose of the paper is to analyse and discuss the concept of biomimetics in contemporary architecture. Special attention is given to the attitude towards nature and environment. Biomimetics provides an information transfer from biology to technical disciplines, such as architecture, with aim to understand natural systems and processes developed through evolution, and to implement them in concepts and structures designed by human. The author proposed and applied methodology for multilevel analysis intended to check various aspects of biomimetic approach to the building perceived as a system.

The notion of biomimetics is presented with regard to architecture. Multilevel theoretical model is constructed, based on 3 basic elements related to systems: structure, metabolism and skin. Specific solutions for each of these elements are distinguished and analyzed, under passive, active and hybrid operation mode. The particular examples of selected architectural objects are presented to illustrate the practical application of the research model.

The author looks at relations of the building and environment, comparing them to biological relationships: parasitism, neutralism and commensalism. The discussion leads to remarkable conclusions and provokes some very interesting questions about the role of architecture. Final conclusions address the issues of innovative perception of the built environment as well as shifting baselines regarding ecosystem, climate and sustainability.

**Keywords:** biomimetics, climate responsive, energy efficiency, sustainable building, climate change.

### Introduction

The purpose of the paper is to analyse and discuss the concept of biomimetics as one of the most actual phenomena in contemporary architectural design. The popularity of the topic may be attributed to the development of close links between biological sciences and the technological development. The second reason why we continue looking for inspirations in nature is the changing attitude towards environment, climate and sustainability. The term biomimetics was first used by Otto Schmitt in 1969 in the context of opportunities arising from applying observations from the field of biology in medical engineering (Schmitt 1969). Since then biomimetics has been fast developing tendency, which provides an information transfer from biology to technical disciplines, such as architecture, with aim to understand natural systems and processes, developed through evolution, and to implement them in concepts and structures designed by human (Gruber 2011). This allows for deeper understanding of natural processes developed through the way of evolution, while the analysis of biological phenomena results with systematic transfer of various construction principles and problem solutions into technical applications (Anthony 2014).

Biomimetic approach to architectural design is related to the ability to draw correct conclusions from the natural systems behavior analysis, such as exchange mechanisms

between external and internal environments, including light, energy, gas and liquid (Widera 2016). The purpose of biomimetic design is to create new, complex solutions, based on the biological systems with the assumption that the simple copies of natural models would not work correctly and the deeper research is necessary (Vincent 2006). The author of the paper proposed and applied methodology for multilevel analysis, intended to check various aspects of biomimetic approach to the building perceived as a system.

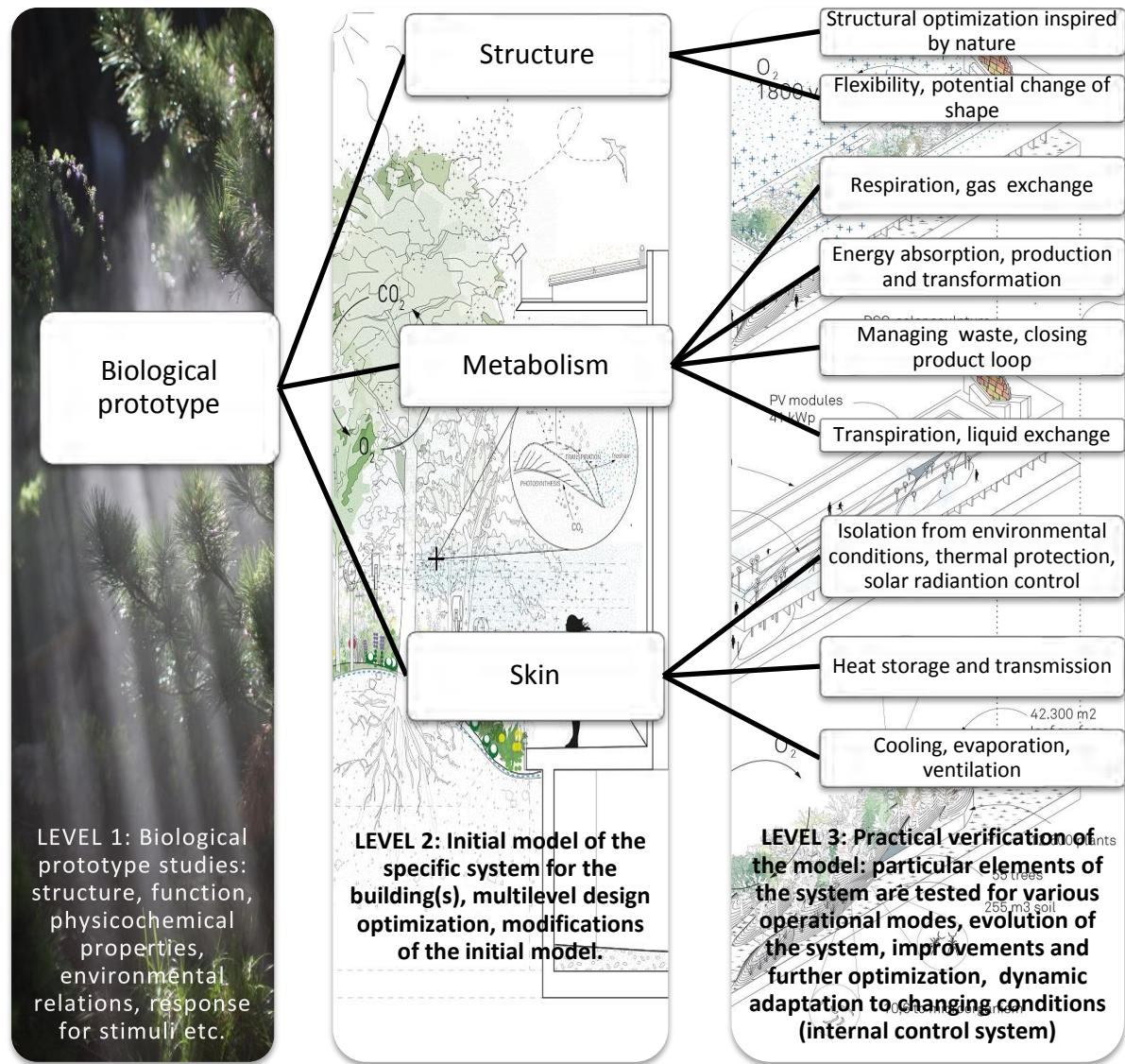


Figure 1. The model of biomimetics in architecture (by Author).

### The model of biomimetics in architecture

In purpose to illustrate the information transfer from biology to the built environment at the beginning of 21st century, the multilevel theoretical model of biomimetics in architecture was constructed (Fig. 1). The starting point of biomimetic design is always a biological prototype. The first level of the model includes studies of selected prototype(s) with respect to its structure, function, physicochemical properties, environmental relations, response for stimuli etc. At the second level the 3 basic elements related to specific system are distinguished as structure, metabolism and skin. Each element is analyzed both

individually and at the system level. Based on the research results, the design optimization process is carried out. Initial model is modified and the developed knowledge is applied to improve the functioning of the building. At the third level passive, active and hybrid solutions are tested to provide practical verification of the model. Particular elements of the system are checked for various operational modes. That leads to the evolution of the whole system, i.e. continuous improvements and optimization. The complete biomimetic architectural system is designed for dynamic adaptation to changing conditions with the application of the internal control system.

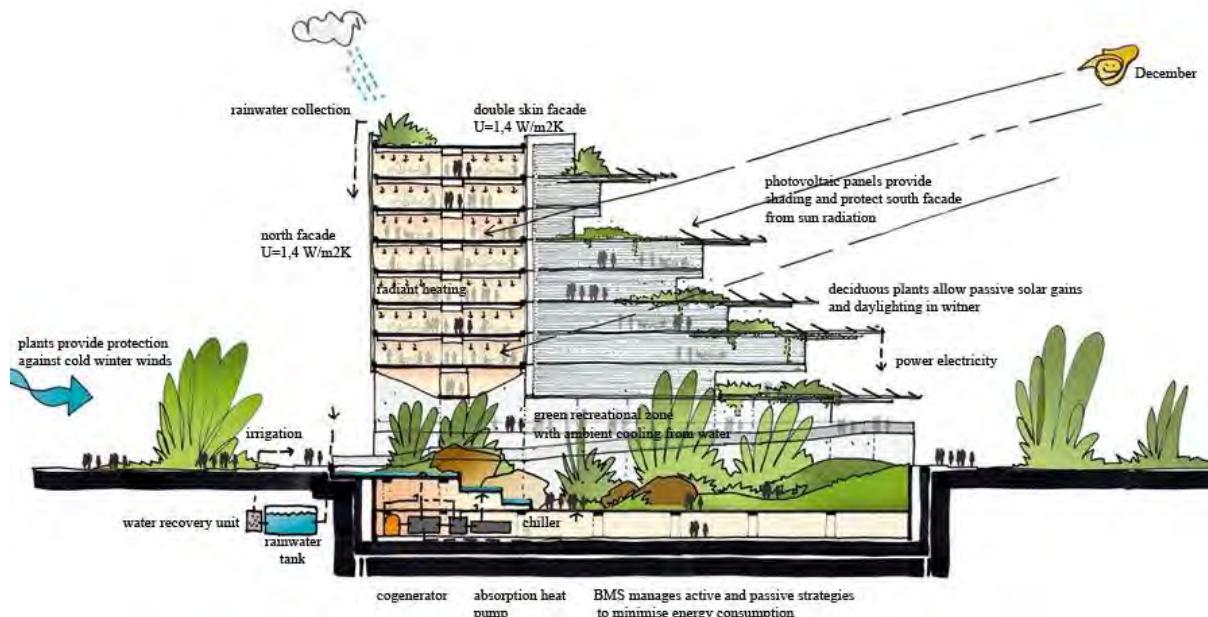


Figure 2. Environmental strategies in Sino-Italian Ecological and Energy Efficient Building (SIEEB), 2005-2006, Beijing, China, designed by Mario Cucinella Architects. © MCA Archive

### **Structure**

Biomimetic structural systems are inspired by the natural ones. Patterns derived from biological prototypes are often optimized with advanced methods, including mainly parametric tools. The important note is the observation of the natural tendency to minimize the need for resources necessary for life (Watts 2001, p 132). Actual technological abilities allow for creation of flexible construction systems that adapt their structure and shape to changing climate conditions (e.g. wind direction and force), similarly as living organisms do. Proposed solutions can be based on passive, active or hybrid concepts. The examples of passive biomimetic structures can be found in buildings designed for particular angle of sun rays during the year, such as Sino-Italian Ecological and Energy Efficient Building (SIEEB), 2005-2006, Beijing, China, designed by Mario Cucinella Architects (Fig. 2). Active structural solutions developed the ability to provide adequate reaction for external stimulus. These are often pneumatic systems, based on synthetic and biosimilar membranes. Complex membrane hybrid systems combine the durability of synthetic membranes with the selectivity of cell membranes, underlying the construction of biomimetic sustainable architecture. The biomimetic structures can also apply advanced strategies for heating and lighting, connected with e.g. phototropism. They are usually combined with adaptive

building skins and properly stimulated metabolic processes within the edifice and its environment.

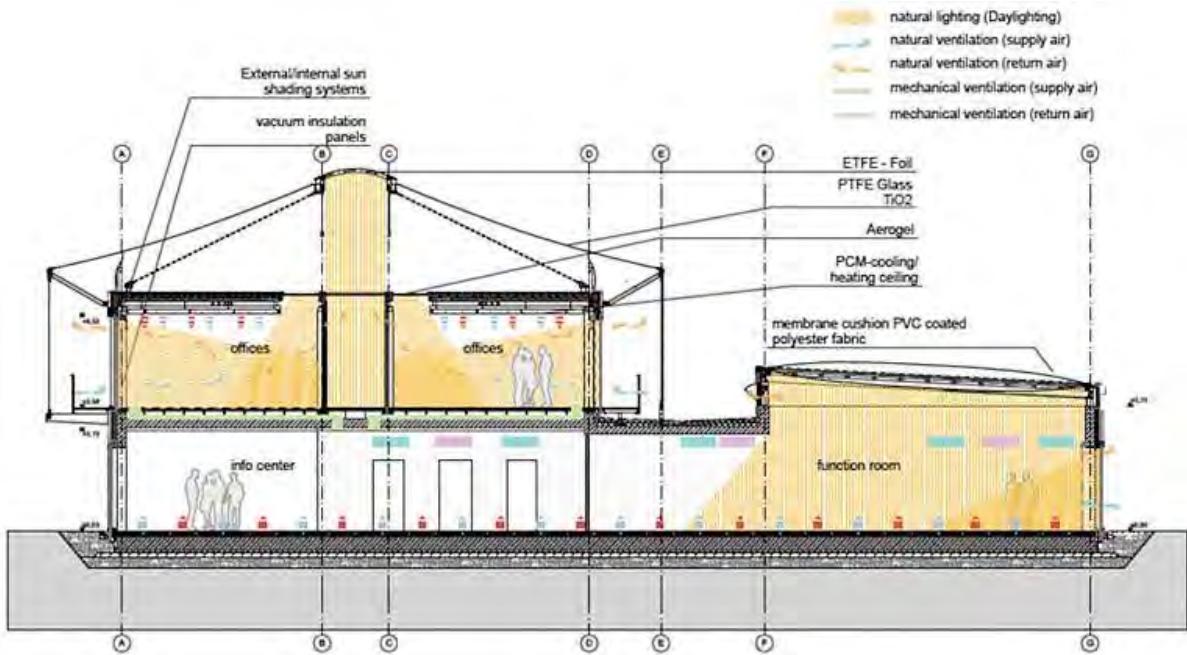


Figure 3. Hybrid thermoregulation in Energy Efficiency Center (2013) Würzburg, by Lang Hugger Rampp Architects and Center for Applied Energy Research (ZAE Bayern, Würzburg). © Lang Hugger Rampp Architects.

### **Metabolism**

Biomimetic systems in buildings involve the exchange of gas (breathing, photosynthesis), liquid (evapotranspiration) and energy (absorption, production and transformation) as well as waste management and closing the loop of materials. Recycling of waste products in order to drive the systems in the building is often considered. Advanced Building Management Systems (BMS) are compared to the nervous system, which provides also a source of inspiration, especially for hybrid solutions (Watts 2011). Some of the very interesting, already existing applications in buildings, are the ones that implement hybrid thermoregulation strategies inspired by the heterothermic organisms. They include e.g. the heat storage in phase change materials as well as heating and cooling with the use of infrared radiation technology (Lang et al. 2014). Such methods were applied and tested in Energy Efficiency Center (2013) in Würzburg, designed by Center for Applied Energy Research (ZAE Bayern, Würzburg) together with Lang Hugger Rampp Architects (Fig. 3). Building hybrid thermoregulation involved Passive Infrared Night Cooling (ZAE Bayern) which uses water flowing freely from the top of the roof and being cooled to the dew point in the nighttime (due to convection and evaporation). This method is completed with adsorption cooling cycle (with a hygroscopic concentrated salt solution) that enables for dehumidification and cooling of the incoming air. The third element of the system is a heat storage layer with phase change materials (PCM), which can store large amounts of heat in the narrow temperature range (because all absorbed heat is required to break the bonds of the crystal lattice). This improves the thermal stability of the premises and helps to avoid undesired short-term temperature rising. Water cooled at night is used for PCM regeneration. Some other examples of metabolic processes are closely related to advanced biomimetic building skins.

## **Skin**

Contemporary adaptive building skins apply schemes of gas, liquid and energy exchange, developed on the basis of biological prototype analysis. Cooling is achieved through controlled natural processes such as radiation, convection and evaporation. Green roofs and façades provide insulation and contribute to better air quality (oxygen partial pressure, humidity). Other research activities in the field of biomimetic building skins involve e.g. integrated hybrid flow control systems for energy harvesting (Dyson et al. 2004). Integrated Concentrating Solar Façade is an active system inspired by phototropism that uses Fresnel lens and polygonal photovoltaic cell. The activation mechanism of photovoltaic cells is linked to solar modules, allowing to adapt the position of the solar modules to the sun rays direction (Dyson et al. 2004). This experimental system is tested in Zero-Energy Corporate Headquarters by SOM and Rensselaer Polytechnic Institute.

Some innovative skin building solutions involve also 3rd generation of solar panels, such as Organic PV Cells with emerging thin films or amorphous silicon, Dye Sensitized Solar Cells, Perovskite cells or Quantum Dot organic/inorganic hybrid PV cells with high absorption nanoparticles. Transparent photovoltaic cells, with Concentrating Photovoltaic and Thermal Hybrid Systems combined with ventilated photovoltaic modules allow for recovery of the part of solar energy that is not converted to electricity (Mocerino 2016).

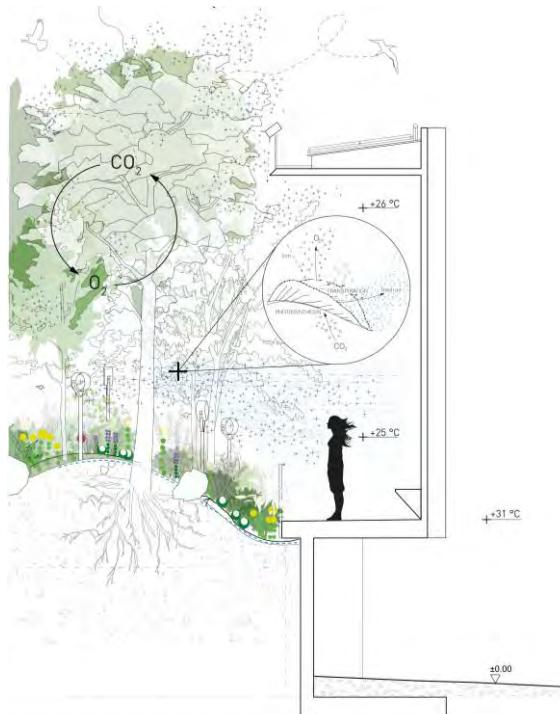


Figure 4. Integration of biology and technology in breathe.austria (Milan 2015) by team.breathe.austria.

## **Practical application of the research model**

Multilevel analysis methodology based on the model of biomimetics in architecture and intended to check various aspects of biomimetic approach to the building perceived as a system was applied to examine the concept of biology and technology integration in breathe.austria project. This edifice was designed and constructed by the interdisciplinary group team.breathe.austria lead by Klaus Loehnert in Milan (Austria Pavilion for EXPO 2015). The biological prototype of the building was the Austrian mountain and foothill forest ecotype. At the first level of the research, the studies of biological prototype involved

structure, function, physicochemical properties, environmental relations, response for stimuli etc. In effect of the initial model analysis results, the specific system for the building was created. This system was analyzed at the second level of the model. The research showed that the controlled interaction between the natural and built environment was developed. This resulted in the climate active building, in which clean, humid and cool air is constantly produced (Fig. 4). It was possible through the combination of leaving and healthy forest ecosystem with high level of biodiversity, i.e. with over 190 various biological species, including flowering plants, small shrubs, mosses and even 12-meter high trees (Terrain 2015). Thus created ecosystem works almost identically as in natural conditions. The only important difference is that the natural processes, such as evapotranspiration and photosynthesis, are supported by active technologies powered by solar energy. Multilevel design optimization and modifications of the initial model were directed towards the achievement of comfortable indoor microclimate. The relevant methods were selected based on an analysis of local bioclimatic conditions (high temperatures during the day, dry air, dust, high CO<sub>2</sub> concentrations due to the large number of visitors).

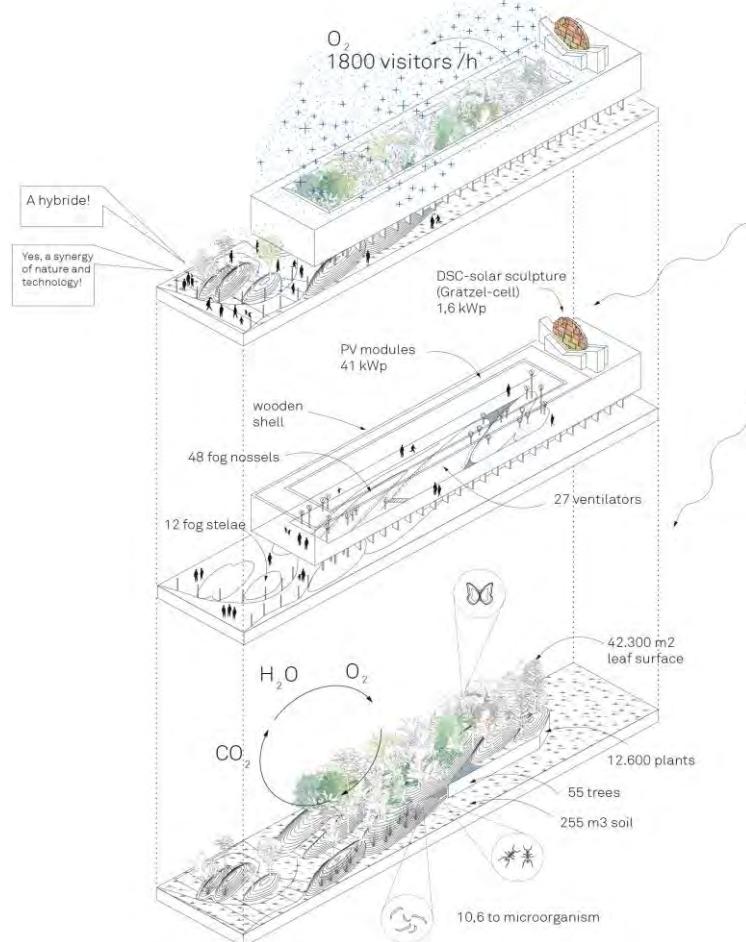


Figure 5. Illustration of biomimetic design concept in breath.austria (Milan 2015) by team.breathe.austria.

At the third level of research, the practical verification of the system was carried out. Particular elements were tested for various operational modes. The internal control system allows for dynamic adaptation to changing conditions, both internal (e.g. the number of visitors) and external (the temperature outside). The response to external and internal conditions is possible with the hybrid indoor air humidification and cooling method that

applies natural evaporation of moisture from the plant and soil surface, aided by the 130 thermodynamic fog nozzles with high-pressure jets. As the part of active technology mode 27 fans improve the air distribution throughout the pavilion. The combination of passive (natural) and active (technological) systems brings effective results. For example the temperature in the pavilion is about 5-7°C lower than the ambient temperature.

The whole building system was designed to enable the evolution. To obtain optimal indoor microclimate conditions, both for ecosystem and human needs, the biological phenomena of photosynthesis was used. The appropriate calculations were carried out for the system optimization. In effect, the amount of oxygen produced by plants corresponds to the breathing demand of 1.800 visitors per hour. For this purpose it was necessary to create the green plants surface with a total value of approx. 43.000 m<sup>2</sup>. The area of ecological growth and metabolic processes in the pavilion equals to 560 m<sup>2</sup> of wooded area (Terrain 2015). Further improvements and modifications were done for the active technological solutions, namely the arrangement and operation of fans, water jets, fog nozzles and fog steles, powered by electricity from PV cells placed on the roof and produced with especially designed Dye Sensitized Solar Cells (Grätzel cells or DSCC, which use the photoelectrochemical process similar to photosynthesis). This innovative concept was in line with the consistent use of biological systems in combination with the currently available technologies (Fig. 5).

### **Relations between the building and environment**

As the building industry represents around 40% of global CO<sub>2</sub> emissions and similar level of global energy consumption, it is crucial to take measures towards significant improvement of relations between the building and the environment (ecosystem). If we compare the previously developed activities in the field of contemporary human settlements to biological relations, in many cases it would be analogous to parasitism. With the knowledge and technological development of today, we should achieve at least the minimal level of well-balanced competition and proceed towards neutralism and commensalism. The ideal option, and hopefully vision of the future biological architecture, would be to learn how to achieve the homeostasis based on symbiosis. The main principle of the relationship between a man and other species inhabiting the same ecosystem, should be to minimize the negative impact of human activity on the environment with regard to its long-term effects. Ability for the climate responsive multilevel building adaptation to the ambient conditions resembles biological models, in which such factors as body temperature and humidity, gas and fluid exchange, flexible change of shape and colour etc., allow for natural adjustment of the organism to the environment without any harmful effect nor excessive resource consumption. In practice, this will enable active metabolism, including e.g. the improvement of air and water quality, building energy management, filtration of pollutants, waste management and reuse, and so on. Building functioning on the basis of solar technologies and active metabolism effects in carbon dioxide absorption and oxygen production, natural cooling, humidification and air purification. Hybrid interaction of biological processes and technology should be seen as a prototype for climate change mitigation and further reduction of negative effects of human activities on the environment,.

### **Conclusions**

The author of the paper analysed and discussed the concept of biomimetics in contemporary architecture. The research showed that the application of biomimetics in

architectural design allows for correct conclusions from the biological systems behavior analysis, in purpose to create new, complex solutions, based on the biological models. Various aspects of biomimetic approach to the building, understood as a system, were checked with the innovative methodology. The model was based on 3 levels. Within the first level, the studies of biological prototype involved its structure, function, physicochemical properties, environmental relations, response for stimuli etc. In effect of the analysis of selected initial model, the specific system for the building was created. This system was analyzed at the second level of the model, where 3 basic elements were distinguished: structure, metabolism and skin. At the third level of research, the practical verification of the system was carried out. Particular elements were tested for various operational modes which resulted with various shape, structure and process optimization. The evolution of the system involved many improvements, e.g. enabling for dynamic adaptation to changing conditions with the use of internal control system. The whole building concept resembles the leaving organism. It combines natural and technological processes in the most effective and efficient way. The main conclusion from the research is that it has been proved that with contemporary knowledge and technology it is possible to create the building that is operating on the basis of multilevel biomimetic model, being safe for the environment and comfortable for users. The novel perception of the built environment is related to shifting baselines regarding ecosystem, climate and sustainability. The role of architecture in the future may evaluate from *sustainable* or *less harmful* relation to *thrive* and *endosymbiotic leaving environment* based on properly developed biomimetic models.

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## References

- Antony, F., Grießhammer, R., Speck T., Speck O., (2014). *Sustainability assessment of a lightweight biomimetic ceiling structure*, Bioinspiration & Biomimetics, 9(1) 2014.
- Dyson, A. H., Jensen, M. K. i Borton, D. N., (2004). *Concentrating type solar collection and daylighting system within glazed building envelopes*. USA, Patent US 7190531 B2.
- Gruber, P. et al. (2011). *Biomimetics - Materials, Structures and Processes: Examples, Ideas and Case Studies*. Berlin Heidelberg: Springer-Verlag.
- Lang, W., Rampp, T. i Ebert, H.-P., (2014). *The Energy Efficiency Center of the Center for Applied Energy Research Würzburg, Germany*. Ahmedabad, Center for Advanced Research in Building Science and Energy, CEPT University.
- Mocerino, C. (2016). *Integration of the Energy and Building Technologies*, Journal of Civil Engineering and Architecture 10 (2016) 1403-1415.
- Schmitt, O. (1969). *Some Interesting and Useful Biomimetic Transforms*. Boston, Proceeding, Third International Biophysics Congress, Aug. 29 - Sept. 3, p. 297.
- Terrain (2015). *Breathe.austria - prototype for future urban practices*, Graz: Terrain.
- Vincent, J. F.; Bogatyreva, O. A.; Bogatyrev, N. R.; Bowyer, A.; Pahl, A. K., (2006). *Biomimetics: its practice and theory*. Interface, 22 August.3(9).
- Watts, B., (2011). *Bettering Biology*. Architectural Digest, 81(2), pp. 128-134.
- Widera, B. (2016). *Biomimetic and Bioclimatic Approach to Contemporary Architectural design on the Example of CSET Building*. In: Nano, Bio and Green – Technologies for Sustainable Future, 16th International Multidisciplinary Scientific Conference SGEM 2016, Conference Proceedings, Vol. II, Albena, Bulgaria, 30 June-6 July 2016, pp 485-492.



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*Design to Thrive*

## Renovating Abandoned Houses for Sustaining a Declining Community in Japan

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**Abstract:** This paper explores efforts to sustain rural communities in the Inland Sea of Japan, which are often referred to as “marginal communities,” especially focusing on the renovation projects of abandoned houses. Uninhabited Japanese wooden houses rapidly decay and negatively affect the community. To prevent this, artists and architects joined to renovate two abandoned wooden houses utilizing local, traditional and recyclable materials and building tectonics while eliminating energy-consuming technologies and materials. The results of this case study present a local prototype for passive low energy house design. Two abandoned houses were renovated. The first was mostly renovated using a DIY approach (except where legally enforced), while the second utilized a contractor. Although the two renovation projects adopted quite different construction schemes, they had common design policies in terms of material preferences and construction waste control. These case study projects revealed that traditional materials and tectonics are still favorable and promising in our era, as they realized the low life-cycle cost and low energy consumption model. Such solutions contribute to preventing the extinction of insular marginal communities and to sustaining the future of our society.

**Keywords:** renovation, rural community, marginal community, the Inland Sea of Japan,

### Introduction

The trend of depopulation and aging communities have been observed in many rural areas in Japan and in other developed countries for decades. These issues have become more serious since the beginning of the 21st century, however, and many rural communities are at stake. The term “marginal community” has emerged, and the issue has rapidly attracted public attention in Japan—especially after the Japan Policy Council issued the so-called Masuda Report (Masuda, 2014). Although some people consider these communities to be less efficient than urban communities, there are still reasons to sustain such areas. These communities can even provide promising ideas for future society, and there are people who hope to move from urban areas to such rural communities.

Following periods of depopulation, there have been discussions of counter urbanization in some European countries—especially in the UK (Cloke, 1985 and Cross, 1990). Japan is no exception; signs of counter urbanism have emerged in rural areas. The Inland Sea of Japan is one of such destination (Yagi, 2010a). Accordingly, this paper explores efforts to sustain such a community located on a small island in the Inland Sea of Japan, focusing on the renovation projects of abandoned houses in the insular neighborhood.

### *The Inland Sea of Japan*

The Inland Sea of Japan, lying between Mainland Japan and Shikoku Island, has 727 islands within a circumference of larger than 0.1 km. It was once renowned for its beautiful landscape,

featuring numerous tourist attractions, and was established as one of the first Japanese National Parks in 1931 (Figure 1). The Inland Sea used to be an important artery of the Japanese maritime economy. Many industries, such as shipbuilding, refining, salt and other chemical industries, flourished in the area, as did most of the communities within. Although about 300 islands are inhabited, many have faced severe depopulation. Very few of the shipbuilding companies and refinery plants remained on some of the major islands following a drastic change of industrial structure, and it is believed that most of the minor and smaller communities will eventually be extinct.

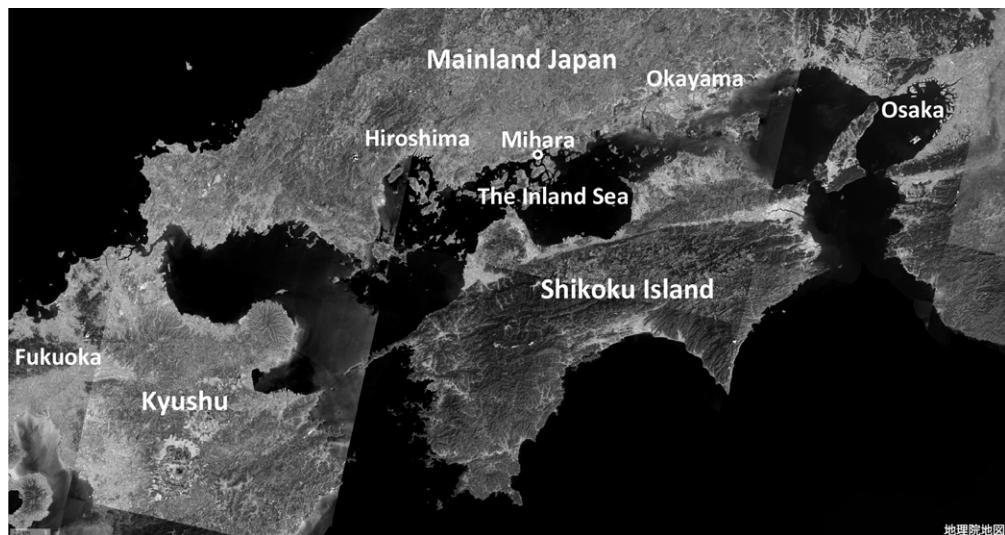


Figure 1. Location of the Inland Sea of Japan.  
Based on the image published by Geospatial Information Authority of Japan.

### ***Subject Community***

The community that this research focuses on is in Kosagijima, which is part of Mihara City in the Hiroshima prefecture. Kosagijima is a small island that is about 3.2 km in circumference and located approximately 3 km south from downtown Mihara City. Although the shipbuilding industry attracted more than 100 residents during the modernization period, the island contains four households and a population of five as of 2017.

The once-flourishing, large-scale shipbuilding enterprise did not last long in Kosagijima, and the population quickly declined. Although the small shipbuilding industry on the island continued until the late 1960s, there has been no manufacturing industry on the island since then. The current major industry there is agriculture; citrus fruits, beans, potatoes and other vegetables are grown. Potatoes used to be the staple food on the island. The residents must make regular journeys to downtown Mihara City in order to purchase daily necessities and acquire medical services.

In 2010, there were 23 houses in Kosagijima. Some of the vacant houses are still visited and maintained by the house owners or by relatives. Many others, however, have been left unvisited for a long time, and two have been almost completely abandoned (Yagi, 2010b).

### ***Case Study Houses***

Uninhabited Japanese wooden houses rapidly decay and start destroying the community (Figure 2). Two houses abandoned in 2010 have already collapsed to the ground, and other uninhabited houses will meet the same fate. To help prevent this, artists, designers and

architects set up a project and team to renovate these uninhabited wooden houses utilizing local, traditional and recyclable materials and building tectonics while eliminating energy-consuming technologies and materials.



Figure 2. Typical uninhabited house almost collapsing.

A private company in the Hiroshima prefecture offered to sponsor the project, and two abandoned houses have been renovated in the community. The first project was mostly renovated using a DIY approach (except where legally required to employ professionals), while the second project utilized a contractor. Although the two renovation projects adopted different construction schemes, they shared fundamental construction policies: a preference for traditional, local, recyclable materials whenever possible; minimal construction waste; and the adoption of passive air conditioning utilizing the microclimate.

### ***Design Build Project Studio***

The first project, a house facing a small inlet port, was initiated in early 2010 (Figure 3).



Figure 3. A vacant house selected for the pioneering renovation project.

The house owner lives in the mainland Mihara City, rarely visits and barely maintains the house. The roof was damaged and leaking, and the interior had started to decay. These problems needed to be immediately handled. However, construction work could not start until the end of 2010.

Although design work was completed by the spring, it took much longer than expected to dispose or hand over the former residents' private belongings. Furthermore, the project team struggled to raise funding and thus elected to do a DIY renovation. Several artists, art

students and architecture students joined the design build project. Because the project team intended to minimize the construction waste throughout the renovation process, the former residents' private belongings remained unused in the house had to be appropriately handled. It took more than six months to clean the house.

Since the project team was required to transport building materials and construction waste by themselves, a minimal amount of new building material was used (Figure 4).



Figure 4. Transporting building materials and construction waste via private boat.

Renovation work finally began at the end of 2010. First, all modern industrialized sidings and interior finishes added to the original structure were taken down. The original clay wall, which was still in good condition, was discovered under the exterior wooden grain metal sidings and plywood interior finishes. Most of the detached building materials and other materials were stored for later reuse (Figure 5).



Figure 5. Damaged Tatami mats were reused for insulation.  
Less damaged floorboards were carefully removed and saved for exterior work.

Concrete blocks were crushed and reused for the pavement base of the entrance approach (Figure 6). Metal sidings were replaced with traditional wooden sidings, which are very popular among Inland Sea communities (Figure 7). The original clay wall was mostly still intact, so we decided to keep it uncovered for humidity and thermal control. A very steep slope right behind the house provided sufficient cold air flow in the summer. The project team successfully removed the air conditioner from this house (Figure 8). The project was completed in spring 2011. The house has since been used as project team's studio space.



Figure 6. Concrete blocks were crushed and reused for the entrance approach.



Figure 7. Wood siding exterior. Fully open toward the water.



Figure 8. No air conditioner to use electricity, but there is a wood burning stove.

### ***Contractor Model***

The second project was initiated right after the design build project was completed. The house owner had not visited the house for a long time because his parents, who had lived there, passed away. The roof of the storage space was also damaged, but the main part of the house was preserved in relatively good condition (Figure 9).



Figure 9. The second vacant house to be renovated.

The renovation design concept for this house changed several times. This project was originally planned to be a guest house for the sponsor company and expected to be remodeled as another design build project. Although the condition of the building structure was much better than the first project, far more furniture and other belongings were left in the house. It took much longer to clean, which was not done until spring 2013. After a series of revisions, the guest house design was mostly finalized by the end of 2013. The project team predicted that construction would start the following spring.

In the meantime, the sponsor proposed to hold an art exhibition in early 2015 to showcase their art collection and encourage the community. The renovation plan was again revised to meet the requirements of the art exhibition. Because the new design would likely not be completed on time, they decided to hire a contractor. However, the fundamental concept of respecting local traditions and materials remained. An old potato storage space under the floor was remodeled as a small gallery to showcase the insular lifestyle (Figure 10).



Figure 10. The gallery utilizing a former potato storage space.

An art piece occupying the premier space in the main room welcomes visitors to the gallery house (Figure 11). Although the main gallery is air conditioned to preserve the artworks, the rest of the house is not air conditioned. Moreover, all light sources were replaced to use LED light bulbs (Figure 12). The exteriors were almost untouched, but the metal siding material was replaced with wooden siding, as done with the first project (Figure

13). Renovation work was completed in February 2015—a month before the exhibition opened. Thousands of visitors came to the small island during the two-month exhibition.



Figure 11. Hiroshi Senju's painting rests in the main gallery. The clay wall was untouched.



Figure 12. Dining and meeting space open to the forecourt.



Figure 13. Exterior with Japanese plaster and traditional wooden sidings.

### ***Eliminating Energy Consumption***

These two examples show how energy consumption can be eliminated at different stages of the renovation process. To avoid dumping personal belongings and minimizing construction waste, the recycling of construction materials on site remarkably reduced the usage of surface

transportation, which consumes a huge amount of fossil fuels. Clay walls covered by the plywood were uncovered and repaired to be utilized as thermal walls. Some of the interior walls were also relocated, utilizing the microclimate to control the breezeways. Both projects successfully eliminated the use of active air conditioners, though carbon neutral biomass stoves were introduced. As a result, we achieved much lower energy consumption.

## Conclusion

The results of this case study present a local prototype for passive low energy house design. Our project members frequently stay in the studio and recognize that our design approach was appropriate for this environment. The sponsor company has established a foundation to help the community on the island, and their staff reside in the gallery house.

These case study projects revealed that traditional materials and tectonics are still favorable and promising in our era. The renovated houses naturally fit in the local context, as they have been there for a long time. They also successfully realized a low life-cycle cost and low energy consumption model. Such solutions can contribute to preventing the extinction of insular marginal communities and to sustaining the future of our society.

## References

- Cloke, P. (1985). Counterurbanisation: a Rural Perspective, *Geography*, Vol.70, No.1, pp.13–23.
- Cross, D.F.W. (1988). *Counterurbanisation in England and Wales: The Migration Evidence*. London: Department of Geography, King's College London.
- Masuda, H. (2014). *The Death of Regional Cities: A horrendous simulation Regional Cities Will Disappear by 2040 A Polarized Society will Emerge*. [online] Japan Policy Forum. Available at: <http://www.japanpolicyforum.jp/archives/politics/pt20140120152454.html> [Accessed 10 Apr. 2017].
- Yagi, K. (2010a). Art on Water: Art that revitalizes Insular Communities Facing Depopulation and Economic Decline, *Nakhara: Journal of Environmental Design & Planning*, Vol. 6, pp.119–130.
- Yagi, K. (2010b). A Multiple Residence Framework for Sustaining an Insular Community, *Proceedings of the 8th International Symposium on Architectural Interchanges in Asia*, pp.663-pp.666.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Passivhaus: The Architectural Typology of Low Energy Housing

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**Abstract:** The growing number of Passivhaus buildings in the UK suggests an increasing acceptance of the low energy design methodology. Post occupancy evaluation shows that the energy use in Passivhaus homes are generally very low, and that running costs are considerably less than standard housing. However, the move to adopt Passivhaus Planning Package (PHPP) as a mandatory standard has been resisted in many areas with a belief that the benefits are outweighed by the limitations imposed on architectural design when using PHPP. Case study analysis of 42 Passivhaus homes has been conducted to examine the architectural typologies that are generated from the use of PHPP in the UK. This research explores the impact of the Passivhaus design approach on orientation, fenestration, size and spatial relationships of the buildings and determines the impact that it has on architectural design. Qualitative research with the occupants of these homes provides a further understanding of the lived experience of Passivhaus and how users adapt to the technical systems that are required to achieve Passivhaus certification. The case study analysis reveals connections between adaptations made in those living in a Passivhaus to achieve comfort, and questions how different this is to standard housing.

**Keywords:** Passivhaus, architectural design, adaptation, case study, overheating

### Introduction

The beginning of the year 2003 saw a rapid growth in the number of Passivhaus projects around the world. It has been estimated that 30,000 Passivhaus buildings have been realised, with the majority being residential projects. The total number of Passivhaus projects in the UK is estimated to be around 400 units (94 projects), 380 of which were residential (at the time of March 2016). However, the move to adopt Passivhaus Planning Package (PHPP) as a mandatory standard has been resisted in many areas with a belief that the benefits are outweighed by the limitations imposed on architectural design when using PHPP. In this research, 42 Passivhaus homes have been surveyed in which 10 projects have been studied in detail to examine the architectural typologies that are generated from the use of PHPP in the UK. This paper explores the impact of the Passivhaus design approach on orientation, fenestration, size and spatial relationships of the buildings and determines the impact that it has on architectural design. Qualitative research with the occupants of these homes provides a further understanding of the lived experience of Passivhaus and how users adapt to the technical systems that are required to achieve Passivhaus certification. The case study analysis reveals connections between adaptations made in those living in a Passivhaus to achieve comfort, and questions how different this really is to standard housing.

## Contextual background

The layout and arrangements of domestic space have been in a constant state of change with the development of technology. It was suggested by Wright (1964) that heating devices, including fireplaces, stoves and chimneys, have influenced social activities and space arrangement in domestic spaces. On the other hand, the mechanical service system has also been developed in line with advances in technology and the socially constructed idea of comfort. The result of this development suggests that a particular lifestyle is shaped by a combination of factors concerning technology, comfort and architecture.

Study on the post occupancy of Passivhaus began during the last decade in Sweden. According to Mlecnik (2012), a considerable amount of German-language research has been carried out regarding occupants' experience. The results showed that the majority of occupants living in Passivhaus expressed high levels of satisfaction in terms of comfort and energy saving. However, recent research has shown a significant risk of summer overheating in Passivhaus in the UK, with 72% of the surveyed Passivhaus households exceeding the benchmark (Tabatabaei S. et al, 2015). The same research also indicated the importance of household behaviour in the prevention of overheating. Since the current Passivhaus standard sets a fixed threshold temperature as the overheating benchmark (25 degrees for more than 10% of the total occupied hours) without consideration of external conditions or household characteristics (such as old age), the design method does not give an accurate prediction of summertime indoor temperature. Rojas's (2015) study of 18 Passivhaus suggested that most significantly exceed the Passivhaus certification criterion (i.e. 10%  $\geq 25^{\circ}\text{C}$ ). The research also found that top-floor flats were much more vulnerable than those on other floors.

Research on Passivhaus tends to focus on energy performance, and very rarely focuses specifically on architectural design. A study focusing on the occupants of a house and their daily interactions with it may thus reveal a deeper connection between architectural design features and users of Passivhaus.

## Sampling and data collection

42 new-build residential buildings occupied since 2011 have been selected to form the basic sampling pool. In examining the 42 projects together with previous literature, five basic categories have been established into which these projects can be grouped. The five categories are floor area, ownership, building type, construction type and bioclimatic region

Table 2. Comparison of the window-to-floor ratio of three case studies

Floor area (m <sup>2</sup> )	No. of projects	Ownership	No. of projects	Building type	No. of projects	Construction type	No. of projects		
<100	15	Privately owned	26	Detached house	24	Timber	26		
100-200	19			Semi-detached	8		12		
200-300	6	Social rental	16	Mid-terrace	10	Mixed	4		
>300	2								
Bioclimatic region	Scotland N	Scotland W	Scotland E	England E & NE	England W & Wales N	Midlands	East Anglia	England SW/Wales S	England SE/Central S
No. of projects	1	2	4	6	5	5	3	6	10

Of the 42 projects, more than half (24 projects) are single-family detached houses, a majority of which are privately owned. The remaining 18 projects are multi-family dwellings, of which six were developed privately. The treated floor area of the projects ranges from 52 m<sup>2</sup> per household to 408 m<sup>2</sup> per household. The majority of the projects have a floor area of around 130 m<sup>2</sup>. The two main structure systems are timber and masonry.

All 42 projects were contacted during the data collection period from March 2014 to October 2015. A total of ten projects (15 households) responded with an overall response rate of 23.8%. Among the ten cases, the seven single-family projects are all detached, privately developed houses. Their areas range from 151 m<sup>2</sup> (House ST) to 219 m<sup>2</sup> (House SA). The three multi-family projects (including DO, SL from the social rental sector and a cohousing project LA) appear to have relatively smaller floor areas ranging from 65 m<sup>2</sup> (House LA 2bedroom) to 102 m<sup>2</sup> (House DO 3bedroom). The multi-family dwellings are either semi-detached houses (Houses DO and SL) or mid-terrace houses (House LA). The ten projects are located across the UK, as shown in the following figure.



Figure 1. Location map of the studied cases

## Quantitative analysis

In the Passivhaus design guide, several design features are highlighted as being the most important in terms of their effect on the performance of the Passivhaus. These are orientation and shading; building form and form factor; U-value; and airtightness. Those factors became the focus of the quantitative analysis. The design recommendations for a Passivhaus include a focus on achieving the standard's energy performance. In comparison, the studied cases exhibit similar properties in the U-value of external envelope and airtightness. The main differences occur in their form factors and orientation.

### ***Orientation and shading***

In the PHPP, the climatic data used to calculate thermal performance is based on 22 climatic regions across the UK, as specified by the BRE. It also makes adjustments for altitude (-0.6 degree for every 100 m increase in altitude). Aside from guidance in the PHPP, a Passivhaus design guide – the BRE Passive House Primer – has also been widely used for building practitioners aiming to achieve the Passivhaus standard. It is recommended in the BRE Passive House Primer that the orientation of a building should aim to maximise its solar gain, which

means the main façade is oriented within 30 degrees south. A poor orientation can increase annual heating demand by 30% to 40% (McLeod et al.).

A majority of the projects (6 houses) are oriented due south. The remainder, with the exception of the SL and SA projects, are oriented within 30 degrees south. The SL project in East Lothian and the SA project in Durham face 57.7 degrees and 46.6 degrees southwest respectively. Very few of the projects have any natural shading from vegetation or adjacent buildings. Cases FO and TO have moderate shading to the west side, and the SL project is heavily shaded from natural sources to its southwest side. Case LA has heavy shading for a low-angle solar path (winter shading) from vegetation on the other side of the river. It can also be observed that every project has adopted other shading strategies such as a roof overhang, deep window reveal, brise-soleil, balcony, canopy and external/internal blinds or curtains. The design to maximise solar gain has evidently been influenced by the requirement specified in the Passivhaus design guide. One exception can be seen in the SL project. This unit containing four flats is not only designed to reside outside the boundary of recommended orientation, but the site is also heavily shaded on the southwest side.

### **Form factor**

Building form and form factor have been used to optimise the floor area, the footprint of the building, the plot ratio and other parameters. They have also been widely adopted to optimise the energy consumption of the building. Generally speaking, a smaller ratio of external envelope area to the volume of the building (A/V ratio) indicates a lower probability of heat loss and more efficient energy consumption. It has been recommended that 'a favourable compactness ratio is considered to be one where the A/V ratio  $\leq 0.7\text{m}^2/\text{m}^3$ ' (McLeod et al.). This principle can be extended to indicate the complexity of building geometry. Because smaller buildings tend to have a higher A/V ratio, it has been recommended that small buildings be kept as simple and compact as possible, whereas larger buildings can have a slightly more complex shape.

This rule simplifies the certification procedure but also means that the performance of individual households varies. Using an estimation calculation tool developed by BRE, calculations have been carried out to examine the form factors of the studied cases. The calculations show that with the exception of the HI and HA projects, the studied cases have all achieved the benchmark of 3 for the form factor. In terms of the A/V ratio, the three multi-family projects, DO, LA and SL, achieved a ratio of no more than  $0.70\text{ m}^2/\text{m}^3$  (0.7, 0.58 and 0.6 respectively), whereas the single-family projects all scored slightly above the average A/V ratio, with the largest occurring in the ST and TO projects.

### **Qualitative analysis**

Following the quantitative analysis of design factors, the correlational analysis below involves a cross-examination between the physical properties of each Passivhaus project and the corresponding interview data. The analysis has gathered the discomfort/problems highlighted in occupants' interviews in order to identify the design issues that contributed to those problems. For the purpose of this paper, one major issue concerning overheating is discussed.

In the interview, moderate or mild overheating was reported as a discomfort in almost all of the case studies in this research, including both the northernmost and southernmost projects. It can be observed that despite the geographical locations or bioclimatic regions of the building, certain design features of Passivhaus buildings make them more vulnerable to

heat, resulting in the overheating issues seen in those projects. The analysis compared the interview data with the design features of each project. The results reveal the three main issues most likely to be contributing to the issue of overheating for eleven households in this research. These are glazing in relation to room size (W/F), the effectiveness of shading and design for natural ventilation.

### ***Glazing in relation to room size (W/F)***

In the PHPP, the criteria for checking overheating is specified as:

The frequency of overheating is the percentage of hours in a given year that the temperature exceeds 25 degree. For Passivhaus certification this must not exceed 10% of the year. (Lewis, 2014 p.58)

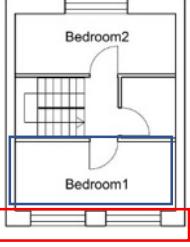
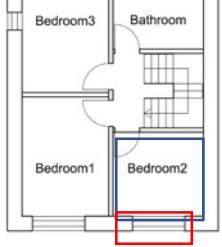
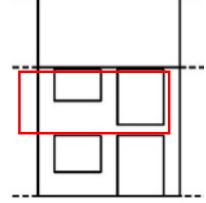
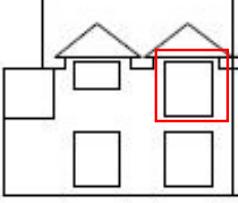
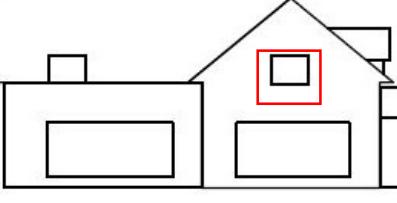
However, when calculating heat gains, the PHPP software distributes heat evenly across the whole building, hence it does not take into account the direct relationship between the size of the windows and the corresponding room size. The certification also means that the overall temperature of the building can remain below 25 degrees for the entire year, while a specific room (usually a small bedroom on the first floor with a large south-facing window) may potentially be above 25 degrees for more than ten per cent of the hours of the year. In this research, analysis was carried out specifically focusing on the window-to-floor ratio (W/F) for the smallest habitable room in each case. The following table (Table 2) shows a comparison with some extremes from the calculation.

All six occupants in the LA and DO projects reported overheating issues. The problem occurs especially in the bedrooms on the first floor. Calculation of the W/F revealed very high ratios of 0.51 and 0.4 respectively in comparison with a lower ratio of 0.21 in the TO project, where no overheating issue was reported. Each project has received its PHPP certification; however, it can be observed that the TO project has a more favourable W/F in each room, which prevents the problem of overheating. The LA and DO projects, in contrast, are more vulnerable to increased temperatures in the summer.

### ***Effectiveness of shading***

In addition to the size of the glazing, in most of the cases natural shading was designed to be just outside the site as a way of maximising the benefit of solar gain. The only building among the case studies to employ natural shading on the south side is the SL project. Not surprisingly, in the interview, the occupants suggested no discomfort/overheating problems in relation to the indoor environment during the summer. For the remainder of the case studies, certain types of external shading were integrated into some of the projects during the design phase. Deep window reveals and roof overhangs were also used quite commonly in most of the case studies. The shading devices used also included internal blinds and/or curtains installed post occupancy in every case study for the purpose of adding both shading and privacy. The integration of various shading devices in each project appeared to be aimed at moderating and eliminating overheating issues; however, the actual observations revealed otherwise. In terms of effectively controlling overheating, the effectiveness of the shading devices employed is more important than simply having a variety installed.

Table 2. Comparison of the window-to-floor ratio of three case studies

Plan			
	LA1 first floor	DO1 first floor	TO first floor
Elevation			
W/F	0.51	0.4	0.14
	LA1 bedroom 1	DO1 bedroom 2	TO bedroom 2

For instance, in the PL project, as the occupants did not understand the function of the shading, they never used it to control overheating. On the other hand, in the HA project, it was suggested by the occupants that the brise-soleil installed was effective in shading most of the summer sun. However, it was insufficient to provide enough shading to control the sunshine at a lower angle in the late afternoon. Thus, the external shading in each of these three projects does not effectively serve its design intention.

Meanwhile, internal shading devices such as blinds or curtains have been adopted in all projects. The effectiveness of these devices for controlling indoor temperature was proved to depend largely on the proper installation of the shading as well as on the behaviour of the occupants. It was observed that the design details of window blinds can play an important role in supporting the occupants' behavioural adaptation to control overheating. Two examples are selected from the case studies as shown below. In most of the case studies, classic 'tilt and turn' windows are used as openable windows. This type of window features two methods of inverted opening. Both opening methods are difficult to use in conjunction with a traditional installation of curtains, and they are even more difficult to use with blinds. This means that natural ventilation cannot be achieved at the same time as shading. This can be a particular problem for Passivhaus in the UK as shading is needed from the low-angle sun during long summer days, while cool air is also needed in the mornings and evenings for ventilation. The window detail in the SL project has further restricted the options in the way that the tilted roof prevents the installation of a curtain rail. However, a more considerate design in the HA project has achieved a better integration of shading and natural ventilation. The design has attached the blinds directly onto the 'tilt and turn' window frame, so that a tilted opening is not disrupted by the drawn blinds.



Figure 2. Comparison of blind arrangement in SL project (left) and HA project (right)

Therefore, it can be observed that the control of overheating using shading devices depends to a great extent on the environmental conditions and also on the occupants' behaviour. The effectiveness of either external or internal shading needs to be considered in the design phase in relation to the prevailing weather conditions, window detail and the occupancy.

### **Cross and stack ventilation**

Natural ventilation using windows on both sides of the house is regarded by all occupants to be the most effective way to control overheating and the most preferred way to ventilate. However, it is worth repeating that in order to sufficiently control overheating by natural ventilation, cross ventilation needs to be designed in conjunction with proper control activities practised by the occupants. In this research, several cases can be listed as examples of such a design feature, including cases CR, FO and HA, as well as the DO project. The overheating problems in these projects were resolved through effective ventilation, with the support of fair cross ventilation and, wherever possible, stack ventilation design and an active adaptation of behaviour in controlling the windows.

Taking CR project for example, in order to control overheating, an observable behavioural adaptation, a newly developed routine of combining natural ventilation, shading and mechanical ventilation was performed:

*[...] In the summer we do open the windows in an intelligent way so early in the morning we open north facing windows on the ground floor, let the cool air come in and walk its way upstairs. So we pull blinds down to keep away the mid-day summer sun out when necessary, we also use the MVHR system to do night time purging. [...] From about mid night through to 6 am, [...] by the morning the house is quite cool. (interview with CR occupant)*

### **Concluding remarks**

The rigour and care that were put into the research design have ensured the results of this research are valid. However, it is important to acknowledge that the existence of a number of limitations during the research design process may have prevented it from achieving more significant findings. Firstly, in terms of the qualitative nature of this research, no environmental measurement was taken to indicate temperature, air velocity, humidity and accurate energy consumption. This decision was made at the beginning of this research in

order to set a clear focus for the experiential data, at the same time to avoid causing any inconvenience to or violating the privacy of the occupants. The data collected have proved to be representative of the occupants' experiences and can be correlated to other quantitative measures (such as building parameters and energy consumption) for the purpose of drawing conclusions. However, the results may have benefitted from further comparison and analysis if environmental measures had been taken at the time of the interview.

Secondly, the significance of this study is limited by the response rate for the chosen sample. In this research, ten projects have been studied. However, the range of project types has given a good sample of the PH community and is fairly representative. It can be stated that a wider study would have enabled a broader testing or a further theoretical saturation of the codes, but would not have revealed any additional categories. While emphasising the rigorous methodological approach of this research, it is also important to acknowledge that the conclusions drawn from cross-case analysis with the interview data and a comparison of the cases remain context based. In addressing comfort issues in design, this paper confirms the risk of overheating in certain Passivhaus in line with previous studies conducted in the UK. The result from this study suggests certain connections between the design recommendations of Passivhaus and the risk of overheating, especially for south-facing houses/flats with smaller area and a more compact form. However, the study also reveals the various behavioural adaptations performed by the occupants, which, if supported by appropriate architectural design, can be exercised effectively to control overheating and to achieve comfort.

## References

- Lewis, S. (2014). *PHPP Illustrated : A Designer's Companion to The Passive House Planning Package*, London : Riba Publishing.
- Mcleod, R., Mead, K. & Standen, M. *Passivhaus Primer: Designer's Guide*.
- Rojas G. et al. (2016). Applying the passive house concept to a social housing project in Austria – evaluation of the indoor environment based on long-term measurements and user surveys. *Advances in Building Energy Research*. 10 (1).
- Tabatabaei S. et al. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, pp. 222-235
- Wright, L. (1964). *Home Fires Burning : The History Of Domestic Heating And Cooking*. London: Routledge & K. Paul,.

# Bridging the Performance Gap

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## Bridging the Theory of Regenerative Design and the Current Building Practice: Evaluation of Regenerative Design Support Tools

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**Abstract:** Although current practices of sustainable design exhibit many improvements on conventional design, they only slow down the degradation of earth's natural systems. The emerging field of regenerative design (RD) and development extends the concept and application of sustainability by shifting the goal from a 'net-zero' to 'net positive' approach and strives to *reverse* the negative impacts. Defining RD is easier than setting measurable performance goals due to the complexity of the topic. However, several RD support tools, serve a significant role in bridging the theory and the current building practice, are emerging to guide the transition. This paper aims to explore the methods and techniques in the current RD tools and to identify their limitation and research gaps. A review of definition and key principles of RD and a conceptual framework called Holistic Regenerative Design Framework are proposed to evaluate the comprehensiveness of RD support tools—REGEN, Eco-Balance, Perkins+Will Framework, Living Building Challenge, and LENSES. The results show that none of the tools are comprehensive enough to clearly guide designers. The paper concludes by characterizing the tools; recommending an approachable way to use the tools together in order to incorporate whole system thinking; and providing directions for future research.

**Keywords:** regenerative design, sustainability, design support tools, green.

### Introduction

The emerging field of regenerative design (RD) and development redefines the goal of built environments, the process of design, and the role of designers. Although the current practices of green design exhibit many improvements on conventional design for conserving resources and reducing the damage to the environment and humans, they only slow down the degradation of earth's natural systems. RD aims to reverse the negative impacts instead of merely slowing them down.

The theory and concept of RD is complex and cannot be easily quantified. It is not easy to set measurable performance goals like the green design approach because it requires thinking of whole systems and interconnectedness of humanity and nature during design process to create living systems that are mutually beneficial and co-evolving. Several RD support tools are emerging to bridge the gap between the theory and current building practice by offering indicators and frameworks. However, there is still a need for future studies to create adequate metrics and methods to comprise whole systems thinking. In the given complexity, this study aims to examine the tools to find a clarity and a practical pathway.

## **Background and Context**

Regenerative design and development as a ‘distinct’ field emerged from an ecological worldview, and its foundation goes back to the 1880s (Mang and Reed, 2012a). The development of the concepts such as ecosystem (Tansley, 1935), living systems thinking (Mang and Reed, 2012a), biophilia (Wilson, 1984), ecological design (McHarg, 1969; Van der Ryn and Cowan, 1996), permaculture (Holmgren, 2011; Mollison, 1988), and regeneration (Lyle, 1994) in the various disciplines built a basis for the emergence of the theoretical underpinnings of RD.

John T. Lyle’s key book (1994) —*Regenerative Design for Sustainable Development*— is the first handbook that outlines RD and its principals and the first key work that extends the concept into the built environment and the field of architecture. He states that humans have replaced nature’s continual cycling system with one-way linear flows and argues that it is possible to regenerate lost ecosystems. Therefore, he defines RD as “replacing the present linear systems of throughput flows with cyclical flows at sources, consumption centers, and sinks” to change the behavior (1994, p.10). According to Lyle, “in order to be sustainable, the supply systems for energy and materials must be continually self-renewing, or regenerative, in their operation. That is, sustainability requires on-going regeneration” (1994, p.10).

After 1995, Regenesis Group studies to develop a theoretical and technological foundation for the approach. With the leadership of Mang and Haggard, the group launched a new book titled *Regenerative Development and Design: A Framework for Evolving Sustainability* in 2016. In 2012, the *Building Research & Information* published a special issue on the topic of ‘regenerative design and development’ that includes 9 key papers<sup>1</sup> covers a wide range of topics. Moreover, Hes and Du Plessis’s (2015) book, *Designing for Hope: Pathways to Regenerative Sustainability*, is one of the key resources in the literature.

## **Defining Regenerative Design and Its Key Characteristics**

There are four main reasons why regenerative approaches are gaining prominence: the need for moving beyond ‘doing less or no harm’ approaches (Pedersen Zari, 2010; Du Plessis, 2012; Cole 2012a; Pedersen Zari, 2012); the push in the industry to achieve higher performance aspirations (Cole et al., 2012; Clegg, 2012); the need for a new paradigm due to the inappropriate thinking processes of the mechanistic worldview (Du Plessis, 2012); and the call for a motivating positive discourse to address the challenges of our time.

There are an increased number of architectural practitioners that have gained experience in green design by producing buildings which achieve the highest level of performance within the Leadership in Energy and Environmental Design (LEED) and other green building programs around the world. “This maturing of green building practice has meant that leading-edge ‘green’ practitioners who have operated at this level are seeking to push much further than the performance aspirations embedded in current assessment methods” (Cole et al. 2012, p.96). Although design professionals are making advances in green building technology, the bigger problems like climate change and biodiversity loss have not been addressed yet (Haggard, 2002). RD aims to creates ‘net positive’ outcomes for ecological, social, and economic development as a whole to reverse the negative impacts.

The literature highlights the importance of moving from a mechanistic worldview — nature as a machine that humans can manage by understanding its parts and accepts that

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<sup>1</sup> Cole, 2012a; Du Plessis, 2012; Mang and Reed, 2012b; Cole, 2012b; Pedersen Zari, 2012; Hoxie et al., 2012; Svec et al., 2012; Cole et al., 2012; and Plaut et al., 2012.

humans are independent and the master of nature— to an ecological one that accepts humans as an integral part of nature and members of the web of life. Moreover, RD manifests a positive narrative to ‘flourish’ the earth as a response to the negative narrative of sustainability that mainly discusses the limits and problems.

### ***A definition of regenerative design***

The term ‘regenerative design’ was introduced by Lyle (1994) and evolved during the last decade. The literature does not have a consensus on the definition of RD and each paper tends to represent its own definition. For example; Mang and Reed (2012a) define RD as “a system of technologies and strategies, based on an understanding of the inner working of ecosystems that generates designs to regenerate rather than deplete underlying life support systems and resources within socio-ecological wholes” (p.2). Furthermore, according to Pedersen Zari and Jenkin (2010), regenerative development “investigates how humans can participate in ecosystems through development, to create optimum health for both human communities (physically, psychologically, socially, culturally, and economically) and other living organisms and systems” (p.3). They define RD as the means of achieving desired outcomes of regenerative development.

This paper defines RD as an approach to shape and form a system (i.e. human ecosystems, communities, buildings, built environments, cities etc.) that seeks to reverse environmental degradation by creating positive impacts, rather than merely causing less damage, to increase the health and wellbeing of humans, other living beings, and ecosystems as a co-evolutionary whole. RD requires an understanding of the fundamental principles of ecosystems to explore how nature designs to regenerate rather than deplete life support systems. It sees place as a core for design and works for understanding patterns of place and ecosystems in different scales from planetary to local in order to find a way to positively participate. The overall objectives of RD are understanding how nature and ecosystems work and participating in nature as a socio-ecological partner to provide positive impacts.

### ***Key characteristics of regenerative design***

The literature was scanned and the ten key characteristics (philosophical departure points) of regenerative design and development were determined:

- Shifting the paradigm: bringing a new mind
- Seeing humans as a part of nature: co-evolution
- Seeking for positive outcomes and improving health and vitality of the co-evolutionary whole
- Offering a hope and positive direction for turning crisis into an opportunity
- Re-defining ‘design’ and the role of designer
- Establishing place as a core and unique entity
- Recognizing values to engage all stakeholders and evoke deep caring for their place
- Exploring patterns, new boundaries and scale
- Acknowledging a new time frame
- Exploring ecosystems to restore, create, and add resilience.

### **Regenerative Design Support Tools: A Bridge Between Theory and Practice**

Because of their significant role in shaping and bridging the theory and the current building practice, the selected five tools —REGEN, Eco-Balance, LENSES, Perkins+Will Framework, and Living Building Challenge— were examined and evaluated in this study. The tools aim to

simplify the theoretical underpinnings and thinking process of RD and to provide guidance and approachable goals for practitioners. The theory of RD introduces several ‘intangible’ new concepts such as whole system thinking, interconnectedness etc. Defining them verbally is easier than setting measurable performance goals due to the complexity of the topic. Therefore, it is necessary to have operational methods, guides, and metrics/indicators to understand, engage, and apply regenerative approaches. In that point, a number of RD support tools are emerging to guide the transition.

Performance assessment and rating systems such as LEED have been dominating the mainstream of green building practice. Their methods are checklist-based and depend on a list of indicators. Although the RD support tools are in their infancy, it is frequently argued that they should be substantially different from checklist-based reductive green and sustainable design assessment tools (Cole, 2012b; Svec et al, 2012; Cole et al, 2012; Plaut et al, 2012). The RD support tools strive to provide a broader framework to integrate the knowledge that comes from previous approaches. The RD support tools are summarized in Table 1 to compare and contrast (Refer to Akturk, 2016 for more information).

Table 1. Summary of regenerative design support tools.

	REGEN	Eco-Balance	Perkins+Will	LBC	LENSES
<b>Developer</b>	BNIM	Pliny Fisk and Gail Vittori	Perkins+Will	International Living Future Institute	CLEAR
<b>Type of Developer</b>	architectural firm	non-profit organization	architectural firm	non-profit organization	non-profit organization
<b>Background</b>	practice + USGBC	the Center for Maximum Potential Building Systems	practice + University of British Columbia	research in EPICenter + BNIM	Institute for Built Environment at Colorado State U.
<b>What???</b>	a data-rich, web-based tool	a design and planning tool	issues and process-based frameworks	a philosophy, an advocacy and a certification tool	a process and a metrics tool
<b>Audience</b>	professionals and community members	professionals and businesses	practitioners of Perkins+Will	all of humanity i.e.: design professionals, contractors, building owners, politicians, government officials	professionals, businesses, government, students and nonprofit teams
<b>Mission</b>	to guide dialogue and help professionals to engage with regenerative approaches	to provide principles for balancing life support systems across life cycle phases	to offer constructive direction to design teams and to generate dialogue for regenerative approaches	to lead the transformation to a world that is Socially just, Culturally rich and Ecologically restorative	to cultivate, empower, and equip change makers to create a regenerative future
<b>Goal</b>	transforming practice toward regenerative approaches	supplying our needs in a regenerative manner	expanding design for positive synergies	a living regenerative future	a thriving living environment
<b>Structure</b>	linking specific strategies to the whole	series of graphics	challenging questions	list of imperatives	overlaid three lenses
<b>Main Categories</b>	Robust and Resilient Natural Systems, High-performing Constructed Systems, Prosperous Economic Systems and Whole Social Systems	Air, Water, Food, Energy, and Materials	Foundation, Sandbox, and Toolbox	Place, Water, Energy, Health & Happiness, Materials, and Equity, Beauty	Foundation Lens, Flows Lens, and Vitality Lens
<b>Verification</b>	no	no	no	yes	no

## Holistic Regenerative Design Framework

This paper proposes an overall framework called Holistic Regenerative Design Framework (HRDF) to visually represent RD and its key attributes (Figure 1). The HRDF highlights the importance of a new kind of understanding of success with both quantitative and qualitative indicators. It has four ‘Essence’ as a framing structure to gather all attributes together: Philosophy, Design Process, Indicators, and Emergence of Regeneration. Each Essence consists of four Categories, and there are sixteen Categories in total. Although the graphic has a linear visual representation, the process is cyclic and continual. The HRDF can be used to both design a project and to evaluate the existing design tools or case studies. In this study, the HRDF was used to evaluate the RD support tools.

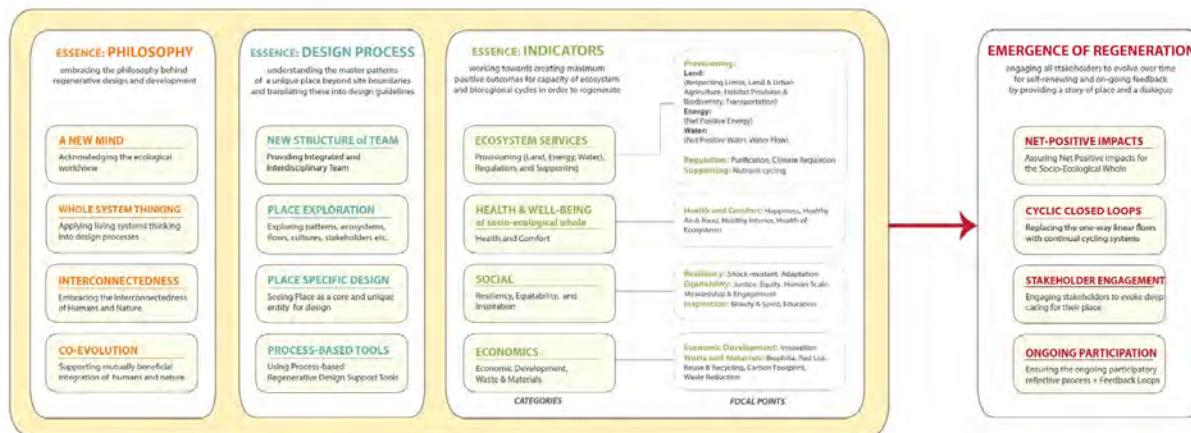


Figure 1. The holistic regenerative design framework.

## Evaluation of Regenerative Design Support Tools

### Methodology

This paper investigates how the tools apply the concepts of RD into design processes, what kind of methods and techniques they offer, and what their gaps and limitations are. The sixteen Categories of the HRDF were transformed into a table format (evaluation sheet) to analyse the tools. An evaluation sheet was filled for each tool (the last versions and original documents of the tools were gathered) as a baseline for the study (Refer to Akturk, 2016 for details of the methodology). The tool evaluation consists of two parts:

- *The Comparison of the Regenerative Design Tools: Support* aims to examine whether the tools address all of the topics mentioned in the HRDF. The overall comparison of the five RD tools was represented in two layers: Addressing and Goal Setting. The Addressing layer is represented by yellow circles while the goal setting is dark pink circles. Both layers have three options depending on their comprehensiveness (e.g. addresses, indirectly address, no explanation) (Table 2).

- *The Comparison of the Regenerative Design Tools: Theory + Practice Methods*, the second part, shows the common methods offered in the tools that strive to apply theoretical concepts of RD into practice (Table 3). The methods and techniques offered in each tool were determined separately and were metaphorically overlaid to determine common ones.

### Findings and Recommendation

The results of the tool evaluation were represented in two tables (Table 2 and 3). Overall, there are three main findings about RD tools: the shared patterns, the well explored topics, and the gaps and limitations of the tools.

First, the RD tools share three patterns. i) The tools are complex and time intensive due to their attempt to deal with complexity. ii) Although the literature of RD rejects the checklist format and element-based approaches in reductionism, the tools include a list of indicators with a different kind of representation. They provide a broader framework to engage with a holistic view and integrate this with a reductionist approach. iii) The tools provide a series of graphics to explain the issues. They emphasize the cyclic processes of RD by using circular shaped visuals. Although this attitude is understandable, it carries the risk of making the diagrams more difficult to comprehend. Second, by using the tool comparisons, the well explored concepts within the RD support tools were determined. They are (represented with black lines in Table 2): A new mind; Interconnectedness, Place exploration and Place specific

design; Building performance metrics such as energy and water. Third, the gaps and limitations of the RD tools were also determined to give a direction for future studies. These gaps are (represented with green rectangles and numbered by the order of importance in Table 2): Ecosystem services, Resiliency and social systems, Stakeholder engagement, Ongoing participation and Co-evolution.

Table 2. The Comparison of the Regenerative Design Tools: Support.

						
CATEGORIES	REGEN (R)	Eco-Balance (E)	Perkins+Will (PW)	LBC (LB)	LENSES (L)	
PHILOSOPHY	A New Mind Whole System Thinking Interconnectedness Co-evolution	       	       	       	       	
PROCESS	New Structure of Design Team Place Exploration Place Specific Design Process-based Tools	       	       	       		Well explored categories
INDICATORS and Focal Points	Ecosystem Services: Provisioning Regulation Supporting Health and Well-being: Social:	                                     <img alt="white circle" data-bbox="318 6285 338				

From a designer's standpoint, it might be difficult to use the five tools together per a project. For this case, using the combination of the LENSES and LBC is recommended. It is crucial to call attention to the gaps in the tools to acknowledge that none of the tools are sufficient to include all aspects of RD.

Table 3. The Comparison of the Regenerative Design Tools: Theory + Practice Methods.

CATEGORIES		HOW TO: COMMON TECHNIQUES	(Sources)	EXAMPLE INDICATORS
PHILOSOPHY	A New Mind	<ul style="list-style-type: none"> <li>- Ecological worldview</li> <li>- Place specific design</li> <li>- Interconnectedness</li> <li>- Flexible and descriptive strategies</li> <li>- Process-based Framework</li> </ul>	(All) (All) (R, PW, LB, L) (E, PW, LB, L) (PW, L)	
	Whole System Thinking	<ul style="list-style-type: none"> <li>- Link specific strategies to whole</li> <li>- Make connections and relationships visible</li> <li>- Outside in Thinking</li> <li>- Holistic Performance Assessment</li> <li>- Sandbox and Toolbox</li> </ul>	(R, L) (R) (L) (E) (PW)	<ul style="list-style-type: none"> <li>- Stewardship</li> <li>- Partnership</li> <li>- Intergenerational view</li> <li>- Education</li> </ul>
	Interconnectedness	<ul style="list-style-type: none"> <li>- Ecosystem understanding</li> <li>- Nested model of the triple bottom line of sustainability</li> <li>- Story of Place</li> <li>- Link specific strategies to whole</li> <li>- Biophilia</li> </ul>	(Indirectly / All) (R, PW, L) (LB, L) (R, L) (R, LB)	<ul style="list-style-type: none"> <li>- Socio-ecological harmony</li> <li>- Co-evolution</li> <li>- Polyvalence</li> <li>- Synergy</li> <li>- Mutualism</li> <li>- Interdependence</li> <li>- Respecting limits</li> </ul>
	Co-evolution	<ul style="list-style-type: none"> <li>- Map multiple benefits of strategies</li> <li>- Place diagram: representation of the interaction between human and natural systems</li> </ul>	(R) (PW)	
	New Structure of Design Team	<ul style="list-style-type: none"> <li>- Interdisciplinary and integrated team</li> <li>- Use 'IDP roadmap' for design processes</li> </ul>	(PW, LB, L) (PW)	
	Place Exploration (Patterns, Boundaries, Scale)	<ul style="list-style-type: none"> <li>- Measuring the flows (historic, current, and future)</li> <li>- Discover broader boundaries</li> <li>- Scale Jumping concept</li> <li>- Pattern Literacy</li> <li>- The Living Transect</li> <li>- Using web-based data to gather information for place</li> <li>- The Place and Flows diagram to explore a place</li> </ul>	(All) (All) (LB, PW) (R, E) (LB) (R) (PW)	<ul style="list-style-type: none"> <li>- Place</li> <li>- Water</li> <li>- Energy</li> <li>- Materials</li> <li>- Ecosystem services</li> </ul>
	Place Specific Design	<ul style="list-style-type: none"> <li>- Assessment of the Flows</li> <li>- Define Unique Place</li> <li>- Story of Place</li> <li>- Be uniquely connected to the place, climate, and culture</li> <li>- Remediate, Repair, Restore and Regenerate a unique place</li> <li>- Use place-based data</li> <li>- Initial Stakeholder dialogue to discover place and create guidelines</li> <li>- Sandbox diagrams</li> </ul>	(All) (All) (LB, L) (LB) (E) (R) (PW) (PW)	<ul style="list-style-type: none"> <li>- Geophysical</li> <li>- Infrastructure</li> <li>- Culture</li> <li>- Human and natural resources</li> <li>- Climate</li> <li>- Transportation</li> <li>- Flows</li> <li>- Land use</li> </ul>
	Process-based Tools	- Guidance for design process	(PW, L)	
	INDICATORS	<ul style="list-style-type: none"> <li>- Series of graphics to explain the approach</li> <li>- List of strategies / Indicators / Imperatives</li> <li>- Qualitative metrics: Scaled from degenerative to regenerative</li> <li>- Rubrics and focal points for each rubric</li> <li>- Vitality Lens and its Planning and Evaluation Worksheet (numeric measurement option)</li> <li>- Guiding Questions</li> </ul>	(All) (R, E, LB) (L) (L) (L) (PW)	N/A
REGENERATION	Net Positive Impacts	<ul style="list-style-type: none"> <li>- Net positive goals</li> <li>- Balance life support systems across life cycle phases</li> </ul>	(R, PW, LB, L) (E)	<ul style="list-style-type: none"> <li>- Net positive water, energy, waste</li> <li>- Positive surplus</li> <li>- Health and Happiness</li> </ul>
	Cyclic Closed Loops	- Represent the importance of cyclic closed loops by creating circular (sphere) diagrams	(R, E, PW, L)	
	Stakeholder Engagement (Evoking Deep Caring)	<ul style="list-style-type: none"> <li>- Stakeholder involvement</li> <li>- Get feedback from stakeholders</li> <li>- Story of Place</li> <li>- Discover shared identity</li> <li>- Guided dialogue</li> <li>- Ensure stakeholder participation in design processes; initial discussion, design charrettes and team meetings</li> </ul>	(R, L, PW) (PW, L) (LB, L) (PW, L) (R) (PW, L)	<ul style="list-style-type: none"> <li>- Stakeholder Engagement</li> </ul>
	Ongoing Participation	<ul style="list-style-type: none"> <li>- Ongoing participatory reflective process</li> <li>- Feedback processes</li> <li>- Whole life cycle</li> </ul>	(E, PW, L) (E, PW, L) (R, E)	

#### LEGEND

R: REGEN, E: Eco-balance, PW: Perkins+Will, LB: Living Building Challenge, L: LENSES

 Techniques explored  
In more than two tools

## Conclusion

As the concept of RD gains prominence, it is anticipated that there will be an increasing demand for more comprehensive and approachable design support tools to guide practitioners aspiring to engage with it. Observing the development and testing of RD tools will certainly lead to shifts in thinking and understanding. Although it is predictable that using the RD support tools requires many more skills and personal transformation, the new skills required to engage RD are still unclear. The other issue is considering how mechanistic and

ecological worldview work together. Moreover, it is anticipated that the concept of ecosystem services will be discussed more in the future due to its significance and lack of exploration. To better explore the concept, the design and development disciplines must coordinate research with the fields of biology and ecology on the application of ecosystem services to the built environment. The question is how will the future studies regarding ecosystem services shape and transform the practice and the tools?

## References

- Akturk, A. (2016). *Regenerative Design and Development for a Sustainable Future: Definitions and Tool Evaluation*. Master. University of Minnesota.
- Clegg, P. (2012). A practitioner's view of the 'Regenerative Paradigm.' *Building Research & Information*, 40(3): 365–368.
- Cole, R.J. (2012a). Regenerative Design and Development: Current Theory and Practice (Editorial). *Building Research & Information*. 40(1): 1–6.
- Cole, R.J. (2012b). Transitioning from Green to Regenerative Design. *Building Research & Information*. 40(1): 39–53.
- Cole, R.J., Busby, P., Guenther, R., Briney, L., Blaviesciunaite, A. and Alencar, T. (2012). A Regenerative Design Framework: Setting New Aspirations and Initiating New Discussions. *Building Research & Information*, 40(1), 95–111.
- Du Plessis, C. (2012). Towards a Regenerative Paradigm for the Built Environment. *Building Research & Information*, 40(1): 7–22.
- Du Plessis, C. and Brandon, P. (2014). An Ecological Worldview as Basis for a Regenerative Sustainability Paradigm for the Built Environment. *Journal of Cleaner Production*, Volume 109: 53–61.
- Haggard, B. (2002). Green to the Power of Three. *Environmental Design and Construction*, March/April: 24–31.
- Hes, D. and Du Plessis, C. (2015). *Designing for Hope: Pathways to Regenerative Sustainability*, New York: Routledge.
- Holmgren, D. (2011). *Permaculture Principles and Pathways Beyond Sustainability*. Australia: Holmgren Design Service.
- Hoxie, C., Berkebile, R., Todd, J.A. (2012). Stimulating Regenerative Development through Community Dialogue. *Building Research & Information*, 40(1), 65–80.
- Lyle, J.T. (1994). *Regenerative Design for Sustainable Development*. New York, NY: John Wiley and Sons.
- Mang, P. and Reed, B. (2012a). Designing from Place: a Regenerative Framework and Methodology. *Building Research & Information*, 40(1): 23–38.
- Mang, P. and Reed, B. (2012b). Designing from Place: a Regenerative Framework and Methodology. *Building Research & Information*, 40(1): 23–38.
- McHarg, I. (1969). *Design with Nature*, New York, NY: Natural History Press.
- Mollison, B. (1988). *Permaculture: A Designers' Manual*. Tyalgum, Australia: Tagari Publications.
- Pedersen Zari, M. (2010). *Regenerative Design for the Future*. BUILD 01/2010; 115:68-69, [Online] URL: [https://www.researchgate.net/publication/261476511\\_Regenerative\\_Design\\_for\\_the\\_Future](https://www.researchgate.net/publication/261476511_Regenerative_Design_for_the_Future).
- Pedersen Zari, M. and Jenkin, S. (2010). Re-defining cutting edge sustainable design: from eco-efficiency to regenerative development. *Sustainable Building Conference (SB10)*. New Zealand.
- Pierce, D. (2015). Information and graphics are provided by personal communication and [Online] URL: <http://c3livingdesign.org/> Accessed: 2/18/2016.
- Plaut, J.M., Dunbar, B., Wackerman, A. and Hodgin, S. (2012). Regenerative Design: the LENSES Framework for Buildings and Communities. *Building Research & Information*. 40(1): 112–122.
- Reed, B. (2007). Shifting from 'Sustainability' to Regeneration. *Building Research & Information*, 35(6), 674–680.
- Regenesis. (2016). *Regenerative Development and Design: A Framework for Evolving Sustainability*, New Jersey: John Wiley & Sons.
- Svec, P., Berkebile, B. and Todd, J.A. (2012). REGEN: Toward a Tool for Regenerative Thinking. *Building Research & Information*, 40(1): 81–94.
- Tansley, A.G. (1935). The Use and Abuse of Vegetational Concepts and Terms. *Ecology*, 16: 284– 307.
- Van der Ryn, S. and Cowan, S. (1996). *Ecological Design*. Washington, D.C: Island Press.
- Wilson, E.O. (1984). *Biophilia*. Cambridge, MA: Harvard University Press.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Are occupants more satisfied with indoor environmental quality in green-certified buildings?

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**Abstract:** Green building certification systems aim at improving the design and operation of buildings. However, few detailed studies have investigated whether green certification effectively leads to higher occupant satisfaction with the qualities of the indoor environment. Building on previous work, we analysed a subset of the Center for the Built Environment (CBE) Occupant Indoor Environmental Quality (IEQ) survey database – featuring 11,243 responses from 93 LEED-rated office buildings – to rigorously explore the relationships between the credits achieved by certified buildings in the IEQ category and the satisfaction expressed by occupants with their workspace and with related factors of indoor environmental quality. We found that the achievement of a specific IEQ credit did not increase occupant satisfaction. Qualitative assessments suggested that there are many reasons for this lack of relationships, many of which are outside the control of designers and beyond the scope of green building certification systems based primarily on design intent. We conclude with a summary of recommendations that design professionals, certification systems, and evaluation methods need to consider for moving us towards more comfortable, higher performing, and healthier green-certified buildings.

**Keywords:** Indoor Environmental Quality (IEQ), Occupant Satisfaction, Green Certification, Post-occupancy Evaluation, Leadership in Energy and Environmental Design (LEED)

### Introduction

Green building certification systems are assuming a prominent role to promote the sustainability agenda in the design and operation of buildings. However, their contribution towards improved satisfaction with indoor environmental quality (IEQ) is still much debated. Particularly in the workplace, the qualities of the indoor environment (heat, light, sound, air quality, etc.) can profoundly impact on occupants' comfort, performance, health, and wellbeing (Huang et al., 2012; Bluysen, 2014). However, despite the assumption that a certified building leads to improved IEQ (USGBC, 2017a), the empirical evidence has often been inconsistent, mostly due to differences in data collection and analysis techniques.

Among studies reporting positive effects of IEQ in certified buildings, MacNaughton et al. (2017) conducted cognitive tests in green-certified and in non-certified but high-performing buildings ( $n= 69$ ). While buildings had roughly equal indoor environmental conditions, cognitive performance was higher in the certified buildings (possibly also due to workplace culture and other non-measured factors). Performing meta-analysis on data from two large field studies, Leder et al. (2016) found that users of green-rated offices tended to rate all aspects of environmental satisfaction more highly than occupants of conventional buildings, although working in a certified office was not necessarily associated with higher job satisfaction. The study also suggested that users of green buildings might be more 'forgiving'

of indoor conditions, as already proposed by Leaman and Bordass (2007). Conversely, other research has emphasized that green certification criteria might not yet be informed by a complete characterization of how physical conditions drive user perception, this resulting in occupants of green buildings seldom showing consistent higher satisfaction with their workplace. For example, Tham et al. (2015) compared the IEQ perception and the prevalence of sick building syndrome (SBS) symptoms and sick leave in a platinum-certified ( $n= 31$ ) and in a conventional office building in Singapore ( $n= 33$ ). Although the certified building was perceived as cooler, and with fresher and cleaner air, it did not have different measured IEQ parameters (physical, chemical, and biological) than the conventional office, nor was any association detected between certification, lower SBS symptoms, and sick leave records.

Some limitations of previous research consist in the use of rather small sample sizes and the reliance on null-hypothesis significance testing (NHST) of differences in mean satisfaction scores, which might bias the practical relevance of conclusions (Cumming, 2014). In response, earlier work by the authors (Altomonte & Schiavon, 2013; Schiavon & Altomonte, 2014) analysed a large subset of the Center for the Built Environment (CBE) survey database featuring 21,477 responses from 144 office buildings, of which 65 were LEED-rated. The results – which were based on estimation of effect sizes, a standardized measure of the magnitude of the differences detected and not just of their statistical significance – showed equal satisfaction with the building, the workspace, and with several factors of indoor environmental quality between users of certified and non-certified offices. These findings were independent of gender, age, office type, spatial layout, distance from windows, building size, work type, and working hours. Conversely, evidence was detected for LEED buildings to be more effective in delivering satisfaction in open-spaces rather than in enclosed offices, and in small rather than in large buildings. Also, tendencies suggested that users of LEED buildings might be more satisfied with air quality and less satisfied with amount of light, and that the positive values of certification may decrease with time. Further research by the authors on BREEAM-rated buildings in UK led to similar results (Altomonte et al., 2017a).

These studies, however, did not include detailed analysis of the associations between user satisfaction and specific IEQ credits. Therefore, this new stage of research sought to assess occupant satisfaction in LEED-rated buildings considering the individual credits achieved in the indoor environmental quality (IEQ) category, the total IEQ points scored, the product and version under which certification had been attained, and the final rating level.

This paper synthesises the results obtained, focusing specifically on the comparisons between occupant satisfaction and individual and total IEQ credits achieved.

## Methods

This study was structured on a mixed-method research design, combining *quantitative* analysis of user satisfaction in LEED-rated buildings with *qualitative* assessments derived from an industry focus group with designers and researchers, our professional judgment, and a comprehensive review of the literature.

The details of the methods and analysis approach are presented in Altomonte et al. (2017b) and in Walker (2015), and we provide only a brief summary here. The dataset, which is described in Table 1, originates from the Center for the Built Environment Occupant IEQ survey database (CBE, 2017), and includes 11,243 responses from 93 LEED-rated office buildings located in US (83) and Canada (10). These buildings were selected since they all hosted office-type activities and administered the survey within two years of certification.

Table 1. Distribution of buildings and occupant responses by LEED product, rating, and version

<b>Product</b>	<b>NC</b>		<b>EB/EBOM</b>		<b>CI</b>		<b>Total</b>	
<b>Rating</b>	Buildings	Responses	Buildings	Responses	Buildings	Responses	Buildings	Responses
Platinum	16	1,186	4	848	5	291	25	2,325
Gold	29	3,472	7	1,456	7	1,746	43	6,674
Silver	8	524	2	556	6	425	16	1,505
Certified	5	148	0	0	4	591	9	739
<b>Version</b>	Buildings	Responses	Buildings	Responses	Buildings	Responses	Buildings	Responses
1.0	3	284	1	80	7	1,602	11	1,966
2.0	15	1,371	2	164	9	899	26	2,434
2.1/2.2	37	3,523	0	0	0	0	37	3,523
2008	0	0	2	491	0	0	2	491
2009	3	152	8	2,125	6	552	17	2,829
<b>Total</b>	<b>58</b>	<b>5,330</b>	<b>13</b>	<b>2,860</b>	<b>22</b>	<b>3,053</b>	<b>93</b>	<b>11,243</b>

LEED NC= New Constructions; LEED EB/EBOM= Existing Buildings; LEED CI = Commercial Interiors

To structure the *quantitative* analysis, we developed 72 pairings – fully described in (Altomonte et al., 2017b) – between CBE survey categories and related LEED IEQ credits. Due to page limitation, the statistical results here reported in relation to the associations between user satisfaction and individual IEQ credits focus uniquely on air quality, temperature, amount of light, and visual comfort. We calculated descriptive statistics and differences between mean and median scores of satisfaction by organizing responses in two groups: buildings that had obtained a specific IEQ credit ( $x_1$ ), and buildings that had not ( $x_0$ ). Since data were ordinal and non-normally distributed, we tested the statistical significance of differences between satisfaction scores in each group with a two-tailed non-parametric Wilcoxon rank-sum test. For all tests, the results were considered statistically significant when  $p \leq 0.05$ . Due to the large size of the samples – which may confound statistical and practical significance – we calculated the effect size by using the Spearman rho ( $\rho$ ) rank correlation coefficient in order to infer the practical relevance of the statistically significant differences detected (Field et al., 2012). Consistent with our previous research, the thresholds provided by Ferguson (2009) were used for inferring small, moderate, and large effects sizes ( $\rho \geq 0.20, 0.50$ , and  $0.80$ );  $p$ -values lower than 0.20 were considered non-substantive, i.e. negligible and non-practically relevant. For analysing the variation of occupant satisfaction based on the total IEQ points achieved, and the product and version under which certification was obtained, we performed ordinal logistic regression specifically focusing on occupant satisfaction with the workspace.

We critically evaluated the findings from the quantitative statistical analysis by *qualitative* assessments. These offered different perspectives to analyze and discuss the design features that might contribute to improved IEQ in office buildings, and frame complex design and construction processes within the dynamic nature of building operations.

## Results

We analysed a total of 72 comparisons between the IEQ categories of the CBE survey and the relative IEQ LEED credits. For a selection of these comparisons, Figure 1 and Table 2 illustrate the boxplots and the descriptive and inferential statistics of results, providing the sizes of sample groups ( $N_0$  and  $N_1$ ), the means ( $M_0$  and  $M_1$ ), medians ( $M_{dn0}$  and  $M_{dn1}$ ) and their differences ( $\Delta M$  and  $\Delta M_{dn}$ ), the two-tailed statistical significance ( $p$ -value) for the Wilcoxon tests, and the effect sizes ( $\rho$ ). Buildings were grouped based on LEED products and versions.

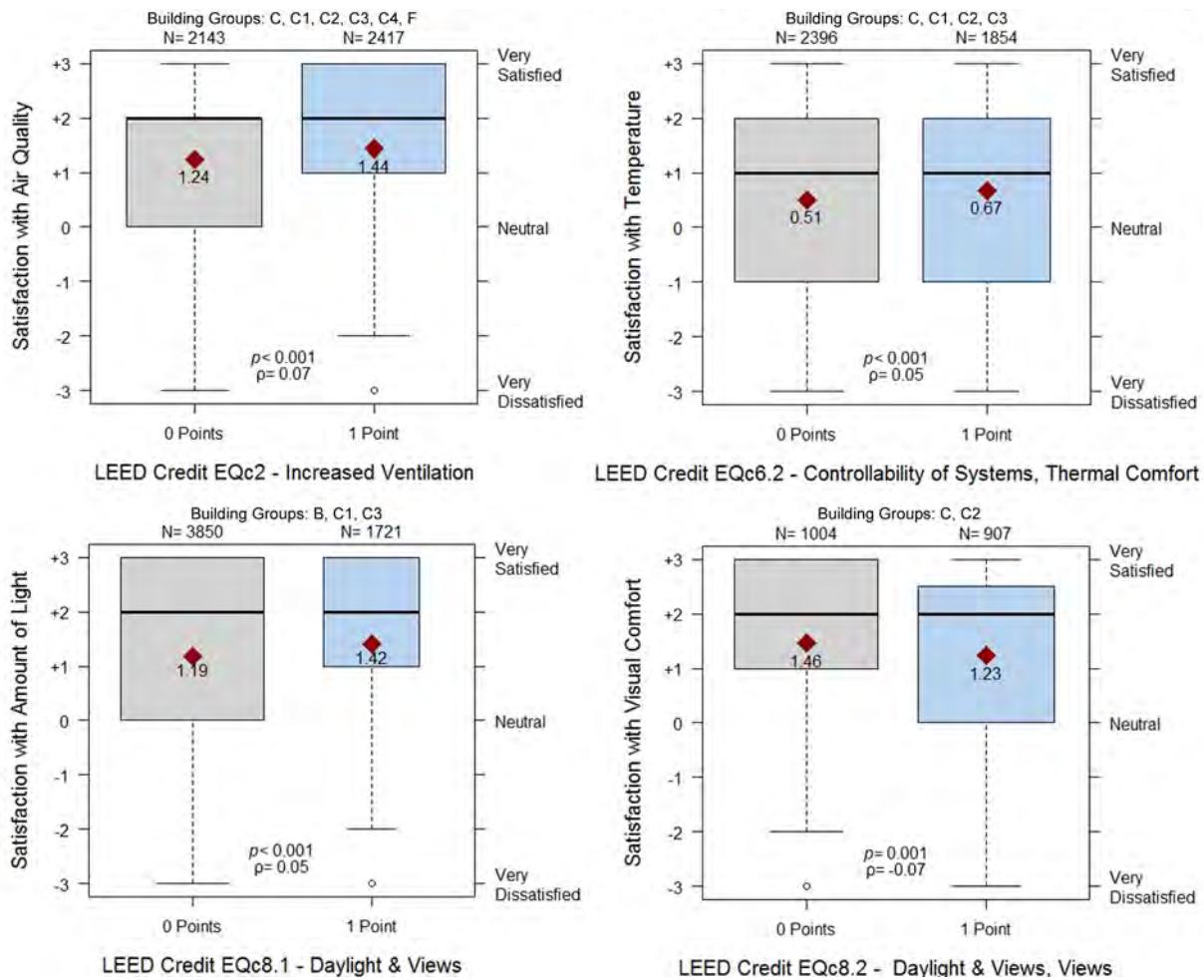


Figure 1. Boxplots for satisfaction with air quality, temperature, amount of light, and visual comfort.

Table 2. Descriptive and inferential statistics for selected comparisons between satisfaction and IEQ credits

Credit	CBE Category	N <sub>0</sub>	N <sub>1</sub>	M <sub>0</sub>	M <sub>1</sub>	M <sub>d<sub>0</sub></sub>	M <sub>d<sub>1</sub></sub>	ΔM	ΔM <sub>dn</sub>	p-value	p
EQc2	Air Quality	2,143	2,417	1.24	1.44	2.0	2.0	-0.20	0.0	<0.001	0.07
EQc6.2	Temperature	2,396	1,854	0.51	0.67	1.0	1.0	-0.16	0.0	<0.001	0.05
EQc8.1	Amount of Light	3,850	1,721	1.19	1.42	2.0	2.0	-0.23	0.0	<0.001	0.05
EQc8.2	Visual Comfort	1,004	907	1.46	1.23	2.0	2.0	0.23	0.0	<0.001	-0.07

p≤0.001= highly significant; 0.001< p ≤0.01= significant; 0.01< p ≤0.05= weakly significant; p> 0.05= not significant

p< 0.20= negligible; 0.20≤ p <0.50= small; 0.50≤ p<0.80= moderate; p≥ 0.80= large

Groups: B=NC 2.0, NC 2.1; C= NC 2.2, NC 2009; C1= CI 2.0; C2= CI 2009; C3= Canada CI 1.0; C4= CI 1.0; F= EB 2.0

The Wilcoxon tests detected statistically significant differences in 49 out of 72 total cases. However, 71 out of 72 comparisons had an effect size of negligible magnitude ( $p < 0.20$ ). The only exception was for a pairing between credit IEQc3.1 - High Performance Green Cleaning Programme and satisfaction with air quality ( $\Delta M_{dn} = -1.0$ ,  $p < 0.001$ ,  $p = 0.27$ ), although this result should be treated with caution since this comparison was based on rather uneven numbers of responses in each independent group ( $N_0 = 368$ ;  $N_1 = 1,877$ ). Graphical analysis of boxplots and inspection of the descriptive ( $\Delta M$  and  $\Delta M_{dn}$ ) and inferential data ( $p$ -value and  $p$ ), therefore, indicates that the achievement of a specific IEQ credit did not have a practically relevant influence on occupant satisfaction with the related IEQ parameter.

For the LEED buildings in the database, the number of IEQ points achieved ranged from 5 to 16. Figure 2 presents the linear regressions for occupant satisfaction with the workspace.

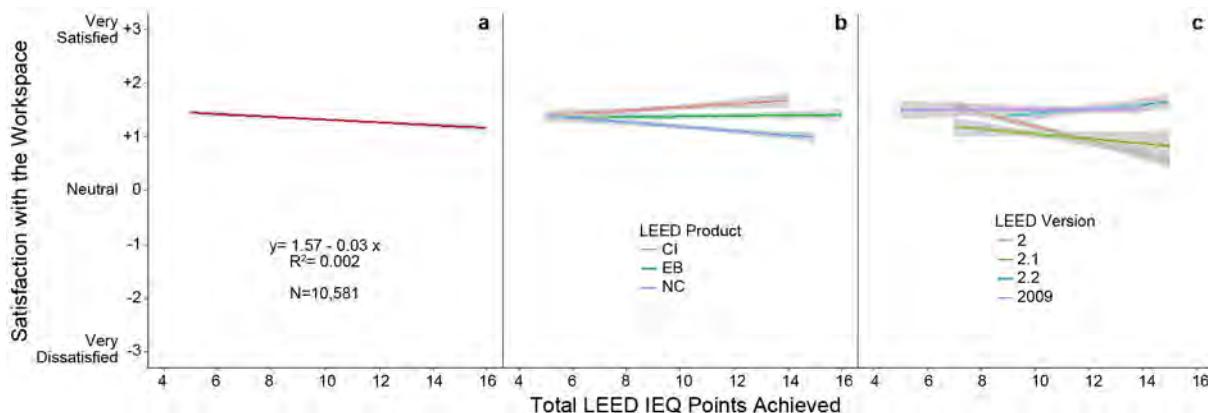


Figure 2. Linear regressions for satisfaction with the workspace based on LEED IEQ points achieved for: a) the full dataset; b) LEED product; c) LEED version. The grey lines represent the 95% confidence intervals.

Surprisingly, the graphs show a tendency for satisfaction with the workspace to decrease as the number of IEQ points increases (Fig. 2a), particularly for buildings certified by LEED NC, while for LEED CI there was a positive slope relationship (Fig. 2b). Also seen is a trend for buildings rated by newer versions of LEED (2.2 and 2009) to perform slightly better in terms of mean satisfaction as the IEQ points increase (Fig. 2c). Overall, the results suggest that the number of IEQ points achieved is not a predictor of satisfaction with the workspace.

Before discussing these results, we want to offer a couple of caveats concerning the limitations of these findings. First, even though we had a large sample, our dataset cannot be considered representative of all certified office buildings and rating systems. Second, even though a specific IEQ credit was not achieved, there may still have been other strategies implemented to address that environmental factor, hence ‘diluting’ the difference between the sets of buildings that have achieved or have not achieved a given IEQ point.

## Discussion

Using our own qualitative investigations and studies found in the literature, this discussion reflects on the many challenges occurring throughout the design, construction, and use of a building that might affect its performance in terms of occupant satisfaction.

### ***Design and certification vs. occupancy and operation***

The design intentions of a project, which is generally the basis for green certification, might be different than the operational characteristics of a building that is then assessed using a survey in a post-occupancy evaluation (in this case, within two years from certification).

Buildings are complex and dynamic, and in the time between design and occupancy many intervening factors can potentially alter the existence – or the performance – of the strategies for which the green rating was awarded. This can begin already during construction, particularly if contractors were not involved in the design phase and have to manage over-complex and inflexible building systems. Also, the operation of buildings requires fine-tuning and adjustments over time to address the performance gaps that often occur between modelled and measured energy use (de Wilde, 2014). It would not be surprising, therefore, that a similar gap might also manifest itself in occupant IEQ satisfaction, regardless of the total amount of IEQ points achieved, or whether a specific IEQ point had been scored or not at design stage. Conversely, the trends for more positive associations between satisfaction with the workspace and total IEQ points attained for newer versions of LEED may be deemed as a reassuring outcome in terms of the progress made by certification systems.

### ***The relevance of green certification metrics for IEQ***

One might question whether the current metrics used for attaining an IEQ credit are even intended to translate into improved occupant satisfaction. In fact, metrics should focus on the user as much as the building. This represents a challenge particularly due to the substantial differences that characterize the modern workplace in terms of spatial needs, task requirements (e.g., occupancy, working schedules, etc.), and user characteristics (e.g., sex, age, habits, etc.). Design criteria that address the demands of a ‘standard’ occupant might, therefore, not capture the intrinsic variability of a random user basis, especially when this is considered over the entire lifetime of a building. For example, rating tools have traditionally focused mostly on how to get the highest quantity of light across the floor area, rather than on the quality of the luminous environment. But there has been improvement. Under the recent LEED version 4 (USGBC, 2017b), in fact, the “Daylight” credit includes the need for “*manual or automatic (with manual override) glare-control devices*”, and the “Quality Views” credit features a description of the composition of external vistas.

### ***Survey measures and IEQ satisfaction***

Occupant surveys generally rely on subjective measures, although perception might at times be disjointed from actual physical conditions (Allen, et al., 2015). Also, sometimes a survey question about satisfaction with an IEQ parameter might be misinterpreted by the subject.

As an example, perceived air quality and temperature are connected and often confounded (Fang et al., 2004). The effectiveness of ventilation strategies may be considered by users as a thermal comfort issue more than a measure to dilute air pollutants. In addition, over time occupants might become ‘desensitized’ to certain stimuli (e.g., odors), or attribute the physical impacts of exposure to an environmental parameter to causes different from their sources. Finally, while meeting minimum air quality standards is a pre-requisite for most certification systems, there are many pollutants that can’t actually be perceived by people. So even if the air might be more polluted, this won’t be reflected in survey responses.

Feedback can also be biased by personal or corporate attitudes, and may vary depending on the time spent in the building and the role that the occupant has in the office hierarchy. Research has also shown that ‘green-branding’ can enhance pro-environmental perceptions (Khashe et al., 2015), and that IEQ satisfaction might be influenced by corporate concerns for energy efficiency (Tsushima et al., 2015).

### ***Acoustics and office layout***

Green rating systems treat each IEQ category independently rather than considering the integrated synergies between them. For example, one challenge is how to balance air quality, thermal, and visual performance with requirements for a satisfactory acoustic environment.

As shown in our previous research on LEED (Altomonte & Schiavon, 2013; Schiavon & Altomonte, 2014) and BREEAM-rated (Altomonte et al., 2017a) buildings, satisfaction with noise and sound privacy is often characterized by low scores. However, this is not entirely surprising considering that LEED has not featured a credit on “Acoustic Performance” until v4.

Research has also revealed a strong association between satisfaction with the workspace, noise, sound privacy, and office layout (Frontczak, et al., 2012). Open-plan layouts have commonly been assumed to promote communication and team-work effectiveness (Heerwagen, et al., 2004). However, open spaces might also be more disruptive, such that the benefits of enhanced interaction might fail to offset the penalties of increased noise and decreased privacy (Kim & De Dear, 2013).

### **Monitoring and feedback**

Some level of continuous performance monitoring and analysis of occupant feedback could be beneficial in bridging the gap between design intents and user satisfaction throughout the lifetime of a building. Although surveys are key techniques to obtain this information in a rapid, responsive, and relatively inexpensive fashion, they might lack in contextual information and continued data gathering (Deuble & De Dear, 2014). Ideally, they should be part of a broader and interdisciplinary set of measurement protocols that could exhaustively capture the functioning of a building (ASHRAE, 2012).

Green building rating systems should also systematically reward mechanisms for continuous building monitoring and occupant feedback to ensure that, following certification, the building continues to operate based on design intentions. We are starting to see this. For example, the USGBC recently launched the LEED Dynamic Plaque, a building performance monitoring and scoring platform that generates continuous benchmarking score under a set of categories, and can provide annual LEED recertification (USGBC, 2017c).

### **Conclusions**

Based on the quantitative analysis of a dataset featuring 11,243 responses from 93 LEED-certified buildings, the achievement of an IEQ credit did not substantively affect occupant IEQ satisfaction, and the total IEQ points obtained had negligible influence on satisfaction with the workspace, independent of the product under which certification was awarded.

Supported by qualitative assessments, these conclusions lead to the following recommendations. For *designers* and *facility managers*: the design phase of a project differs from the post-occupancy evaluation stage, requiring direct involvement in performance and feedback monitoring to fine-tune operating strategies and transfer best practice to the building industry. For *green certification systems*: the metrics to attain IEQ credits need to better represent reliable indicators of occupant satisfaction. For *evaluation methods and tools*: surveys rely on subjective measures assessing the perspective of the user, but are best used if supported by physical measurements and in-person interviews to holistically appraise building performance; also, satisfaction might be driven by factors other than IEQ parameters, such as time spent at the workspace, attitudes, expectations, workplace culture, etc.

There is no ‘silver-bullet’ for a satisfactory and healthy work environment. Given the dynamic nature of buildings, the complexity of the users, the diverse and evolving demands of the workplace, and the need for these factors to be effectively monitored and analysed, there are still many challenges that the green building industry needs to tackle to promote indoor environmental qualities conducive to satisfaction and wellbeing. However, if sustained by advancements in research and design practice, green rating systems can offer significant opportunities towards better, more comfortable, higher performing, and healthier buildings.

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### **References**

- Allen, J., MacNaughton, P., Laurent, J., Flanigan, S., Eitland, E., Spengler, J. (2015). Green buildings and health. *Current Environmental Health Reports*, 2, pp. 250-258.
- Altomonte, S. & Schiavon, S. (2013). Occupant satisfaction in LEED and non-LEED certified buildings. *Building and Environment*, 68, pp. 66-76.

- Altomonte, S., Saadouni, S., Kent, M., Schiavon, S., (2017a). Occupant satisfaction in BREEAM and non-BREEAM certified office buildings. *Architectural Science Review*, in press.
- Altomonte, S., Schiavon, S., Kent, M., Brager, G. (2017b). IEQ and occupant satisfaction in green-certified buildings. *Building and Environment*, under submission.
- ASHRAE (2012). *Performance Measurement Procedures for Commercial Buildings: Best Practices Guide*. Atlanta: ASHRAE.
- Bluyssen, P. (2014). *The Healthy Indoor Environment*. Oxon: Routledge.
- CBE (2017). Livable Analytics. [Online] Available at: <http://www.cbe.berkeley.edu/survey> [Accessed 18 March 2017].
- Cumming, G. (2014). The new statistics. *Psychological Science*, 25(1), pp. 7-29.
- de Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41, pp. 40-49.
- Deuble, M., De Dear, R. (2014). Is it hot in here or is it just me? Validating the post-occupancy evaluation. *Intelligent Buildings International*, 6, pp. 112-134.
- Fang, L., Wyon, D., Clausen, G., Fanger, P. (2004). Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. *Indoor Air*, 14(s7), pp. 74-81.
- Ferguson, C. (2009). An effect size primer. *Professional Psychology*, 40(5), pp. 532-538.
- Field, A., Miles, J., Field, Z. (2012). *Discovering Statistics Using R*. London: Sage.
- Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., Wargocki, P. (2012). Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air*, 22(2), pp. 119-131.
- Heerwagen, J., Kampschroer, K., Powell, K., Loftness, V. (2004). Collaborative knowledge work environments. *Building Research & Information*, 32(6), pp. 510-528.
- Huang, L., Zhu, Y., Ouyang, Q., Cao, B. (2012). A study on the effects of thermal, luminous, and acoustic environments on environmental comfort. *Building and Environment*, 49, pp. 304-309.
- Khashe, S., Heydarian, A., Gerber, D., Becerik-Gerber, B., Hayes, T., Wood, W. (2015). Influence of LEED branding on building occupants' pro-environmental behavior. *Building and Environment*, 94, pp. 477-488.
- Kim, J., De Dear, R. (2013). Workspace satisfaction: the privacy-communication trade-off in open-plan offices. *Journal of Environmental Psychology*, 36, pp. 18-26.
- Leaman, A., Bordass, B. (2007). Are users more tolerant of 'green' buildings?. *Building Research and Information*, 35(6), pp. 662-673.
- Leder, S., Newsham, G.R., Veitch, J.A., Mancini, S., Charles, K.E. (2016). Effects of office environment on employee satisfaction. *Building Research & Information*, 44, pp. 34-50.
- MacNaughton, P., Satish, U., J.G., Cedeno Laurent, Flanigana, S., Vallarino, J., Coull, B., J.D., Spengler, Allen, J.G. (2017). The impact of working in a green certified building on cognitive function and health. *Building and Environment*, 114, pp. 178-186.
- Schiavon, S. & Altomonte, S. (2014). Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings. *Building and Environment*, 77, pp. 148-159.
- Tham, K.W., Wargocki, P., Tan, Y. F. (2015). IEQ, occupant perception, prevalence of sick building syndrome symptoms, and sick leave in a Green Mark Platinum-rated versus a non-Green Mark-rated building. *Science and Technology for the Built Environment*, 21, pp. 35-44.
- Tsushima, S., Tanabe, S.-I., Utsumi, K. (2015). Workers' awareness and indoor environmental quality in electricity-saving offices. *Building and Environment*, 88, pp. 10-19.
- USGBC (2017a). *This is LEED. Better buildings are our legacy*. [Online]. Available at: <http://leed.usgbc.org/leed.html>. [Accessed 11 February 2017].
- USGBC (2017b). *LEED v4*. [Online] Available at: <http://www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version> [Accessed 18 March 2017].
- USGBC (2017c). *LEED Dynamic Plaque*. [Online]. Available at: <https://www.leedon.io/index.html>. [Accessed 19 March 2017].
- Zagreus, L., Huijzen, C.; Arens, E.A., Lehrer, D. (2004). Listening to the occupants: a web-based indoor environmental quality survey. *Indoor Air*, 14(s8), pp. 65-74.
- Walker, K. (2015). *Indoor environment quality in LEED buildings: understanding conditions affecting performance*. MSc in Architecture. University of California, Berkeley.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Mind the Gap; Methodology Discussion of the Extraction and Analysis of Pilot Phase Data to Generate Multi-Configuration Household Behavioural Profiles

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**Abstract:** This paper constitutes the conclusion of a three-month pilot study, concluding March 2017, performed in a CfSH level 5 housing projects in Lincolnshire, UK. The study uses purpose designed activity and occupancy logs, climate tracking and monitoring of interior environment through the use of data loggers. The research's final output uses occupancy tracking by introducing self-observation and its translation to energy consumption by its integration into multiple occupancy calculation methodologies to investigate these results within the post-pilot study phase. The pilot study constitutes the development of these methods according to each house's occupants and the research objectives. The study aims at generating multi-configuration household behavioural profiles through extracting a comprehensive full set of data, including room functions, activities and factors that contribute to energy consumption by balancing the use of logs and participant comfort. The research undertakes a bottom-up survey, assessing consumption information of frequently used equipment in the house and calculating variable total consumption in accordance with the occupancy and activity logs. In addition, the use of an initial semi-structured interview that was undertaken to address the phenomenological causes that underline the observed behaviour, as well as account for non-quantifiable factors of behaviour. The findings of this study have shown patterns of behaviour that are atypical of usual design assumptions as well as a variety of household combinations that interact uniquely with their buildings.

**Keywords:** Behavioural Profiles; Performance Gap; Occupancy log; Code for Sustainable Homes (CfSH)

### Introduction

Agencies in the UK began with rolling out regulations to affect citizens' energy consumption. By adjusting how houses are constructed and how users interact with their building through cost manipulation (Odeyale et al, 2013; Warren, 2014) and enforcing regulations for planning and construction. After the development of Eco-Homes and its later iteration, Code for sustainable Homes in 2007, in March 2015 BRE announced the phasing out of CfSH and the use of the previously known as code level four as the base level for construction until 2016 (GOV, 2015; Department for Communities and Local Government, 2015). However measured performance post-occupation needed improvement and this caused the surfacing of PROBE studies 1995-2002 by CIBSE followed by Building Performance Evaluation funding (Tse and Colmer, 2014). As of writing this paper in 2017, housing standards are at a tipping point following the new optional building regulations which still use the previous version of SAP and the optional ability to construct houses based on any of the international or national standards such as the newly developed Home Quality Mark (HQM and BRE, 2015). During that transitional shift in regulation, the final reports for the building performance evaluation program and the performance gap studies by InnovateUK and Zero Carbon Hub (ZCH) as well as partner universities and industry specialists were published ending a phase of "proving the existence of the performance gap" and in a way, initiating the age of bridging the gap during the transitional and recommendations period (Tse and Colmer, 2014; ZCH, 2015; Digital Catapult, 2016; Pannell, 2016). This change in regulation left the

industry with a number of projects that were still under construction and ones that already exist with a set of issues that contribute to the performance gap as summarized by the ZCH end of term report (Zero Carbon Hub, 2013). Since the newly introduced Home Quality Mark has to conform to the Standard Assessment Procedures' (SAP) regulations included in Part L of the planning permissions process (HQM and BRE, 2015), it still faces the same issue of calculating user behaviour. A problem unlikely to change since the methodology implemented within SAP existed in CfSH, will exist part of building regulations post-2016 standards' review and will exist when Home Quality Mark is fully launched. Thus it remains a persistent issue for researchers, designers and assessors to work towards solving this problem.

Within the context of BREEAM building codes (CfSH and the upcoming HQM), energy calculations are accounted to achieving a reduction in emissions based on the calculations done within the SAP's technical document/ application. Said calculations, mainly within SAP's occupancy calculation (Henderson and BRE, 2008) and tables 9 within the SAP document (ref) regarding space heating which disregard personal comfort and variations in ambient space temperature (BRE and DECC, 2014), whilst serving as a benchmark in the design process, upon post-occupancy evaluation, the benefit of a probabilistic model would be needed for comparison to validate the real life trend against calculations and thus be able to decide whether the performance gap was due to short-sightedness within SAP or if users' behaviour was too unpredictable for a fixed or dynamic model to estimate (Richardson et al., 2010; Gruber and Prodanovic, 2012; Blight, 2015).

Occupant behaviour is attributed to a number of theories, following or a mixture of theories of planned behaviour Ajzen, 2011, and environmental physical probabilism (Kaiser and et al, 1996), both of which were observed through the methodologies to be discussed in the following sections. Starting at a macro scale with the choice of living in an eco-house by following an assumed theory of self-selection (Michelson, 1977). How user behaviour within their dwelling can be recognized through the models of planned behaviour; addressing the premise that behavioural beliefs, normative beliefs and perceived control over their personal comfort by being able to alter their habitat (Borden and Schettino, 1979; Ajzen, 2011; Blight, 2015). Finally, complimented by probabilism (Kaiser and et al, 1996), a midway point between environmental deterministic and possibilistic factors. The assumption that users are likely to perform actions due to a deterministic environmental factor, however their personal comfort, external criteria and free choice determines whether or not they are likely to do it (Borden and Schettino, 1979).

Examples of these factors that have been previously established are internal and external climate; predictive mean vote of personal comfort; architectural layout and spatial functions; occupancy patterns; age factors; employment and associated routine. The range of factors that operate within these theories are impractical to empirically quantify as they change depending on the conditions surrounding the subjects as well as flow with their own perception and experience of space (Parrys, Saelens and Hens, 2011; ElNokaly & ElSeragy, 2012). Thus the researcher operated on the concept that behaviour of residents of eco-houses who share the values of self-selection and planned behaviour would have similar operational norms, whilst factors such as their age, employment and occupancy patterns would vary due to probabilistic factors that could not be isolated but perhaps regressed into consumption trends that would serve as a comparative baseline for design or post-occupancy evaluation. However, a limitation to this research is to account for the variable occupant numbers per dwelling, their employment and their age would create a variation in results that cannot be considered statistically significant on a large scale without acquiring a wider sample and testing them in further research that is not constrained by time. Thus analysing it on a case-by-case basis, and allowing for the creation of a methodology and toolkit to be used would allow for expanded research and exploration of further scenarios (Pustejovsky, 2015).

### **Background to “EcoHouses” Project and Pilot study**

The pilot study was chosen as a proof of concept to the literature mentioned previously, that whilst it is agreed that user behaviour deviates from predicted SAP models, household configuration also impacts that condition (Yao and Steemers, 2005). The premise being that age and employment have a direct

impact on users' routines and thus have an impact on the total energy consumed accordingly. Hence, it was essential to recruit a set of comparable houses in terms of design and construction standards with the variable being the demographic types of users inhabiting it. In addition the research's overall aim is to streamline this process into a simple and affordable methodology that can be performed as part of a routine post-occupancy study thus within the methodology section, a number of low-tech and budget-aware solutions used to start this process and assess their viability.

To satisfy the conditions mentioned above, the researcher approached a set of privately owned houses in Lincoln, UK's Long Leys Urban Village, roughly 1.2 miles from city center. The project; composed of thirteen houses provided a fertile research opportunity due to a number of factors. The houses are built up to code level 5 standard of CfSH (November 2010) using SAP 2009, constructed and partially inhabited by the end of 2014 and, were advertised as eco-housing with low operational costs, self-sustenance and passive house design with a feed-in tariff to entice potential buyers (Elnokaly and A.J. Martin, 2014).

The housing project, located in the East Midlands, is a private development, privately owned by its current residents that were intended to be a step towards sustainable developments by its developer. Built on an area of brown land within a designated urban village within the borders of Lincoln city, the project had to satisfy a high performance rating in order to gain planning permission. The site is composed of thirteen privately owned three and four-bedroom semi-detached houses built using three various layouts and floor areas, but facing the same orientation, built up to the same standard and acquired identical SAP ratings in both design and evaluation stages. The houses studied in this research are built using two of the layouts, labelled B and D in table 1, three and four bedroom houses respectively with identical floorplans in each case. Due to constraints from the developer the exact figures for the second layout were not released, however it was assured that the released SAP rating was identical to the design specifications.

Table 1 As-Designed vs. As-Built

Dwelling type	As-Designed SAP rating	As-Built SAP rating
Layout B (three bedrooms)	99 (A)	99 (A)
Layout D (four bedrooms)	97 (A)	97 (A)



Figure 1 Site and Floor plans and participation rate

The houses were constructed to reduce reliance on mains electricity by providing a calculated 1024.5 kWh of photovoltaic generated electricity per year and 1158.8 kWh of water heating annual that feeds into a combination boiler (SAP Printout, 2015). The house utilizes two systems for heating, a combination boiler of efficiency 88-89.01% and electric underfloor heating (Compliance Report, 2015; SAP Printout, 2015; Vaillant, 2017). The first disperses its heating load through radiator panels distributed throughout the house. It is notable that these panels are ill-placed (thermostat is situated close

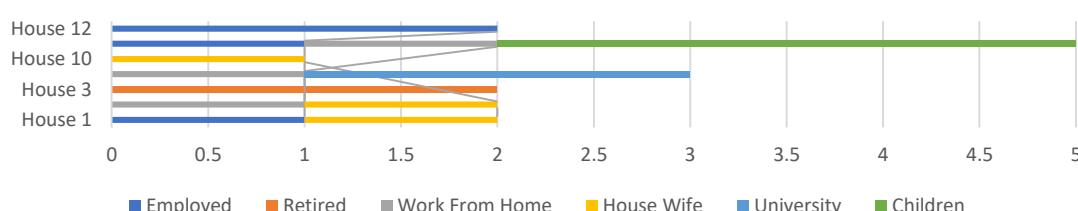


Figure 2. Occupancy and employment values within the case study, from interviews and recruitment

to the panels) causing false-feedback and disturbances within the operation and performance costs of the house. In addition, the houses are occupied by a diverse number of configurations, as shown in fig 2, varying between retired couples, working couples, parents and mixtures of the previous, with a general age range between 40 to mid-sixties. However due to confidentiality, residents' ages are grouped based on NHS age groups within the project.

## **Methodology**

To counter the aforementioned problems, the pilot study of this research project started off by identifying a number of tools, some used previously and others created for this task to generate a large amount of data that can be used within this research to draw relationships and weed out irrelevant and negligible aberrations in behaviour.

The research relies heavily on the research subjects' self-observation of their behaviour and activities through the use of: 1) Daily room occupancy logbooks, 2) Daily activity logbooks, 3) Footfall plan of movement during a typical day, the details of each tool will be further discussed in the following section. The researcher also conducted a number of interviews; based on a modified version of a Building Use Study (CIBSE, 2012) in addition to a number of transcendental phenomenological (Moustakas, 2010) questions that require the users to identify behaviours they routinely or subconsciously partake in. In addition, a bottom up survey of all electric equipment inside the house was performed and mapped on the building's floor plan.

In summary, the research will follow a mixed method research investigation (HO et al., 2006, Cohen et al., 2011). Globally the research will be conducted in the format of an investigative cross-case analysis (Simons, 1996, VanWynsberghe et al., 2008), to ultimately deduce the most prominent factors of user behaviour and how they affect buildings designed using the current UK methodology, SAP under the Code for Sustainable Homes level 5 and compared against data gathered from the Building Use Study and data gathered through this research. Individually, by using empirical data from building performance analysis reports and measurements (Digital Catapult, 2016). Qualitative data gathering through various forms of interview and usage logs (Geer, 1991, Witzel, 2000, Turner, 2010; Elnokaly & Keeling, 2016), and their conversion into comparable and analyzable quantitative values that are to be used within statistical modelling (Dixon-Woods et al., 2005).

However, in addition to gathering a large set of quantitative data, the researcher investigates using a structured interview method with open-ended questions to investigate phenomenological and perception based responses that could account for some of the observed behaviour through logbooks and an experimental procedure. The interview's structure also adopts a modified Building Use Study (BUS) Survey, to extract more perception based question. The research will validate the results obtained from the research-modified interview against the results obtained from the validated results returned by the BUS Methodology group. The BUS methodology has been developed by survey firm Building Use Studies and refined by CIBSE (CIBSE, 1997; CIBSE, 2012). It is used to extract quantitative responses regarding building quality, design and comfort (Pretlove and Kade, 2016). The logbooks are a 30-minute time step chart of activities and room occupancy designed to be filled easily by the participants, they monitor their own activities by filling in the respective time slot, that would be used by the researchers to create a time-plot of probabilistic behaviour and how it would contribute to consumption. The researcher also asked the occupants to participate in an experimental self-observation procedure (Rodríguez et al., 2002; Elnokaly & Martin, 2014)), the footfall is marked on a floor plan of their respective houses and given the intensity of lines, the researcher can compare the findings to current occupancy analysis software to identify the gap in assumed versus actual behaviour.

## **Semi-Structured Interviews**

The researcher's first task was to gather demographic, quality of life and transcendental phenomenological information regarding the users' perception of their life and actions in their current dwelling. As well as identify the possible motives behind self-selection of their current dwellings and decisions of probabilistic and planned behavior. The use of a semi-structured interview provides the

benefit of delivering a concise set of questions directed towards gathering data which are both usable for comparison within standardized quality of life surveys such as BUS surveys. Whilst allowing the researcher the freedom to gather subjective knowledge to reflect on the literature and identify limitations and possible avenues for future research. The data also provides the researcher with routine and detailed interactions that are essential to translating logbooks into tables of actions as a method of validation. In addition, recording the users' fixed routines and automated system would serve its purpose in the next phase of this project when translating system operations into energy consumption. The interviews were in the form of a 15 – 30-minute set of questions divided into 1) understanding of the house's sustainable features, 2) Lighting: behaviour and use of artificial lighting, 3) Thermal comfort: self-selection and planned behavioural data regarding their choice of residence and occupancy patterns. Followed by the same questions used within an ARUP BUS survey (CIBSE, 1997; CIBSE, 2012) however following the same grading system and by adding an open-ended response to where the participant has to elaborate in their own words as to why they chose a particular answer.

Some of the scaled data from the structured portion of the interview are shown in figure 2, validating the original claim that user experience varies between the different houses. However, the use of this data can prove to be misleading without support from transcendental phenomenological data such as the background of understanding of these systems, how they were taught to use it, who manages thermal comfort in the house and so on. Quotes from the interviews depicted in Table 2 allows the researcher to assign certain behaviour to lack of knowledge and observe how it changes throughout the study to rule it out as an aberration or a significant impact on building operation. The following excerpts from the interviews gives the research an additional dimension to allow for the analysis of socio-psychological as previously mentioned by gathering transcendental phenomenological data acquired by self-perception of their environment.

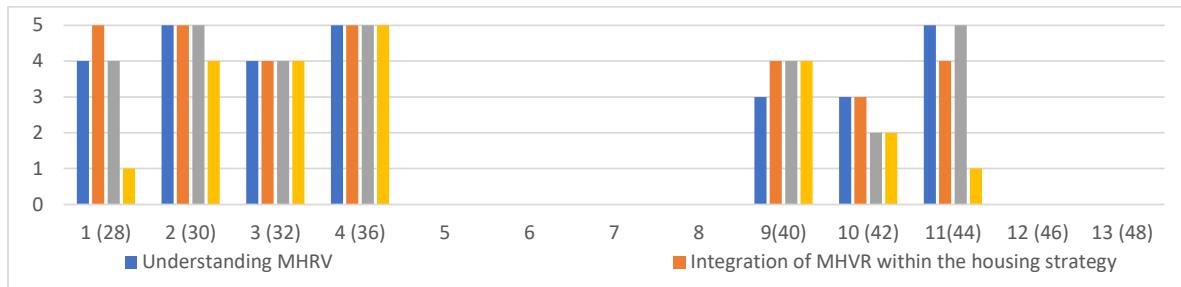


Figure 3 Summary of the house's technology and understanding section of the interview (Researcher's own work)

Table 2 Quotes that support various assumptions and validate information gathered through the logs

<i>How well do you understand the integration of MHRV in the passive strategies &amp; active heating solutions of the house?</i>
"Not well, however my husband maintains all the systems"
"We attended a course on operation of eco-houses in Grimsby so we could know the basics of the heating and heat recovery system. We are still not entirely sure how it works but we're learning"
"We have only lived here for the duration of one summer so we are not entirely sure how the building performs yet. It was quite warm so we did not need to operate any of the systems"
<i>Time of day when you start turning on the lights?</i>
All houses mentioned that they found that their lighting behaviour depends on real daylight hours, that information was validated by reviewing activity and occupancy logs.
<i>How long have you lived in this house? Is this your first high performance/ecohouse?</i>
"We used to live in a Victorian style house with 5 bedrooms that used to get quite cold and would run up quite a bill for heating. We decided to invest in a house like this hoping to cut down on bills especially now that we live alone after our children moved out"
"I used to own another property that was marketed as ecohouse, I moved here to be closer to the city and closer to work"

### Occupancy and Activity Log Books

The use of log books relies on users' ability to reflect on their activities and document them within a simple time-step/room sheet. This low-tech affordable approach combines the benefits of easily accessible resources and the need for users to recall their activities to the best of ability. Other methods such as the use of electronic trackers or using phone tracking software are a cause for privacy concerns and possible discomfort, in addition to substantial cost increase, thus they were rejected despite the possible benefits of implementation. The time constraints and man hours involved, however constrained the number of logs to two per month that would be distributed due to the busy lifestyles of the occupants as well as to prevent loss of interest. The users are required to fill two weeks per month of typical behaviour (or atypical behaviour in case of national holidays and visitors) totalling an average set of twenty-four (24) collections per log category per house per year. Upon reviewing the literature and similar research done before, the researcher observed that subjects are not likely to change their activity within one given hour, thus a high resolution profile of activities was neither feasible nor productive in this case. The researcher chose a resolution of 30-minute time-steps, with activities that occupy less than a time-step assessed on a case-by-case basis to identify their impact within the larger picture within the time frame of a single day and the accumulation within a year.

Translating that data from an analogue form to digital was done by the use of an excel sheet using the same headings, however the data was translated by identifying the maximum number of occupants in the house and inserting a corresponding digit to identify the number of occupants within a room or performing a certain task per time-step. By using the following equation, the excel sheet automatically calculates the maximum occupancy in dwelling at a certain time-step, this is required to avoid conflicts that arise due to doing multiple activities within the same interval using  $If \sum Occ_{a-e} > Max_n \text{ Then Occupancy} = Max_n, \sum Occ < Max_n \text{ Then Occupancy} = \sum Occ$  where  $\sum Occ_{a-e}$  is the total occupancy count of rooms a-e is.  $Max_n$  is the maximum number of occupants known to be available in the house at the time?

Figure 3 Data Translation procedures through excel sheet. (Researcher's own work)

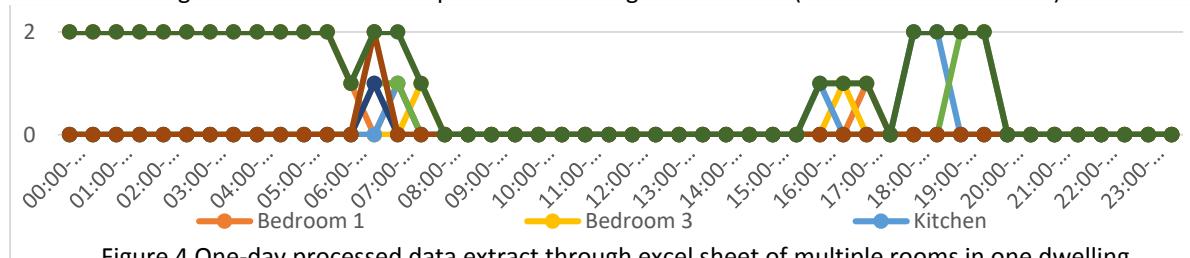


Figure 4 One-day processed data extract through excel sheet of multiple rooms in one dwelling.  
(Researcher's own work)

### Data Loggers

In order to validate the variance in control of the internal environment, the researchers used climatic data loggers placed in key areas of the house, for example, the kitchen and study, which were identified as areas of maximum occupancy. The fluctuations in temperature allow the user to identify environmental cues that influence the occupants' choice to alter internal temperature or trigger any of the automatic systems in place. Currently the research has only monitored one house due to cost and gear restraints. However this has been previously identified as a restraint and additional monitoring equipment has been ordered to continue monitoring the other households. The researcher has used

RHT10 Extech for the first portion of monitoring whilst a requisition for MX1101 (Onsetcomp, 2017) bluetooth data loggers from HOBO was placed part of the development choices after the pilot study.

### **Conclusion**

The pilot phase concluded by April 2017 laying the way for the second phase of this project and continuation of data gathering. The use of activity logs so far has been successful, given the enthusiasm and environmental awareness of occupants, and thus their eagerness to participate in this research. The research team is working on developing a digital method of inputting that data through web-based application as well as self-tracking applications that can be carried mobile for further testing. Data logging is an essential tool and proved to be the highest cost in carrying out this type of research and thus might dissuade others from participating in this kind of research. Extended results of this phase would be published in a later paper, however at this juncture previous hypotheses regarding demographic configurations and their potential impact on consumption have been supported by occupancy and data logger information. Further research is required in order to aggregate these data sets into usable information that can be refined into calculation methodologies as well as the need for expanded research and acquiring of data sets by other researchers to generate a large enough sample for computational analysis. During the handling of the interviews and logbook material, the researcher had to cast away preconceptions of behaviour, adapting Husserl's take on phenomenological research to maintain objectivity of findings (Lowes and Prowse, 2001). Due to the sheer amount of data per household, trends have started to emerge in the form of occupancy patterns, that allow the team to isolate behaviour that is not part of the norm. However, data gathering needs to continue to conclude a year in order to acquire a dataset that is inclusive of different seasonal and climatic changes. Progressing occupancy data to match with consumption data is the next stage since the passive and low-energy devices do not reflect readily with assumed SAP calculations or typical documented behaviour.

### **References**

- Ajzen, I. (2011). The Theory of Planned Behaviour. In: P. Van Lange, A. Kruglanski and E. Higgins, ed., *Handbook of Theories of Social Psychology: Volume One*, 1st ed. pp.438-459.
- Ajzen,I. (2011). The theory of planned behaviour: Reactions and reflections. *Psychology & Health*,26(9),pp.1113-1127.
- Blight, T. (2015). Low-Energy Domestic Architecture: The Impact Of Household Behaviour On The Expected Energy Use Of Passive House Dwellings. PhD. University of Bath Department of Architecture and Civil Engineering.
- Borden, R. and Schettino, A. (1979). Determinants of Environmentally Responsible Behavior. *The Journal of Environmental Education*, 10(4), pp.35-39.
- BRE and DECC (2014). The Government's Standard Assessment Procedure for Energy Rating of Dwellings.
- Build Energy. (2017). The Home Quality Mark Archives - Build Energy. [online] Available at: <http://www.buildenergy.co.uk/category/the-home-quality-mark/> [Accessed 10 Jan. 2017].
- Compliance Report (2015). Building Regulation Compliance Report. MES Solutions.
- Department for Communities and Local Government (2015). Housing Standards Review Summary of Responses.
- Digital Catapult (2016) Building data exchange. [online] Available from: <http://buildingdataexchange.org.uk/> [Accessed 22 February 2016].
- Dixon-Woods, M., Agarwal, S., Jones, D., Young, B., and Sutton, A. (2005) Synthesising qualitative and quantitative evidence: A review of possible methods. *J Health Serv Res Policy*. 10(1) 45–53B. Available from: <http://hsr.sagepub.com/content/10/1/45.short> [Accessed 25 February 2016].
- Elnokaly, A. and A.J. Martin, B. (2014). The impact of the UK governments spending review into the Feed in Tariff (FIT) on the installation on photovoltaic panels in the residential sector. *World Journal of Science, Technology and Sustainable Development*, 11(2), pp.102-116.
- Elnokaly, Amira and Elseragy, Ahmed (2012) Historic city centres as catalysts for wider sustainable urban regeneration. In: *Requalifying the Built Environment: Challenges and Responses*. Hogrefe Publishing GmbH Merkelstr. 3, 37085 , Göttingen, Germany. ISBN: 9780889374300
- Elnokaly, Amira and Keeling, Ian (2016) An empirical study investigating the impact of micro-algal technologies and their application within intelligent building fabrics. *Procedia: Social and Behavioral Sciences*, 216. pp. 712-723. ISSN: 1877-0428

- Geer, J. G. (1991) Do open-ended questions measure 'salient' issues? *Public Opinion Quarterly*, 55(3) 360.
- Gill, Z., Tierney, M., Pegg, I. and Allan, N. (2010). Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research & Information*, 38(5), pp.491-508.
- GOV (2015). Planning update March 2015 - GOV.UK. [online] Gov.uk. Available at: <https://www.gov.uk/government/speeches/planning-update-march-2015> [Accessed 13 Sep. 2016].
- Gruber, J. and Prodanovic, M. (2012). Residential Energy Load Profile Generation Using a Probabilistic Approach. 2012 Sixth UKSim/AMSS European Symposium on Computer Modeling and Simulation.
- Henderson, J. and BRE (2008). A review of the relationship between floor area and occupancy in SAP. BRE.
- HQM and BRE (2015). Home Quality Mark Technical Manual. 2nd ed. [ebook] BRE. Available at: <http://www.homequalitymark.com/filelibrary/HQM--December-2015-.pdf> [Accessed 12 Feb. 2017].
- Kaiser, F. and et al (1996). Environmental Attitude and Ecological Behavior. [online] Available at: <http://files.eric.ed.gov/fulltext/ED409179.pdf> [Accessed 10 Nov. 2016].
- Lowes, L. and Prowse, M. (2001). Standing outside the interview process? The illusion of objectivity in phenomenological data generation. *International Journal of Nursing Studies*, 38(4), pp.471-480.
- Michelson, W. (1977). Environmental choice, human behavior, and residential satisfaction. Nairobi: Oxford.
- Moustakas, C. (2010). Phenomenological research methods. 1st ed. Thousand Oaks, Calif: Sage Publications
- Onsetcomp (2017). MX1101 | Onset HOBO Data Logger. [online] Onsetcomp.com. Available at: <http://www.onsetcomp.com/products/data-loggers/mx1101> [Accessed 12 Dec. 2016].
- Oyedele, Lukumon and Regan, Martin and Meding, Jason von and Ahmed, Ashraf and Ebohon, Obas John and Elnokaly, Amira (2013) Reducing waste to landfill in the UK: identifying impediments and critical solutions. *World Journal of Science, Technology and Sustainable Development*, 10 (2). pp. 131-142. ISSN: 2042-5945
- Parys, W., Saelens, D. and Hens, H. (2011). Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices – a review-based integrated methodology. *Journal of Building Performance Simulation*, 4(4), pp.339-358.
- Pustejovsky, J. (2015). Measurement-comparable effect sizes for single-case studies of free-operant behavior. *Psychological Methods*, 20(3), pp.342-359
- Pretlove, S. and Kade, S. (2016) Post occupancy evaluation of social housing designed and built to code for sustainable homes levels 3, 4 and 5. *Energy and Buildings*, 110(January), 120–134.
- Richardson, I., Thomson, M., Infield, D. and Clifford, C. (2010). Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings*, 42(10), pp.1878-1887.
- SAP Printout (2015). Full SAP Calculation Printout. MES Building Solutions.Simons, H. (1996) The paradox of case study. *Cambridge Journal of Education*, 26(2) 225–240.
- Tse, P. and Colmer, M. (2014). Innovate UK Building Performance Evaluation: Overview of Programme Portfolio. InnovateUK.Available at: [https://connect.innovateuk.org/documents/3270542/19792080/BPE\\_Overview%20of%20the%20programme%20portfolio\\_Nov%202014](https://connect.innovateuk.org/documents/3270542/19792080/BPE_Overview%20of%20the%20programme%20portfolio_Nov%202014) [Accessed 13 Apr. 2017].
- Turner, D. (2010) Qualitative Interview Design: A Practical Guide for Novice Investigators. *The Qualitative Report*, 15(3)
- Vaillant (2017). Vaillant ecoTEC plus 615 VU GB 156/5-5 Boiler Manual | Plumbing Manuals. [online] Plumbing Manuals. Available at: <http://www.plumbingmanuals.com/vaillant-ecotec-plus-615-vu-gb-1565-5-boiler-manual/> [Accessed 16 Apr. 2017].
- VanWynsberghe, R. and Khan, S. (2008) Cultivating the under-mined: Cross-case analysis as knowledge mobilizationForum Qualitative Sozialforschung / Forum: Qualitative Social Research
- Warren, P. (2014). A review of demand-side management policy in the UK. *Renewable and Sustainable Energy Reviews*, 29, pp.941-951
- Witzel, A. (2000) The Problem-centered InterviewForum: Qualitative Social Research
- Yao, R. and Steemers, K. (2005). A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings*, 37(6), pp.663-671.
- ZCH (2017). Performance Gap. [online] Zerocarbonhub.org. Available at: <http://www.zerocarbonhub.org/current-projects/performance-gap> [Accessed 19 Apr. 2017].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Discrepancies between theoretical and actual heating demand in Scottish modern dwellings

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**Abstract:** The study reports on the differences between the actual heat consumption profiles of twelve dwellings monitored for four years and their predicted heat demand profiles as calculated by the UK Government's Standard Assessment Procedure (SAP). This monitoring methodology analysed the selected homes over 4 years of occupation leading to a longitudinal study. Using descriptive statistical metrics this paper considers different groupings and normalisation methods to understand differences in heat demand. It uses this methodology to compare predicted over delivered energy over longer occupation periods. The results demonstrate that the compliance SAP model, incorrectly estimates heat demand by up to one and a half times that recorded in these dwellings. It also concludes that analysing energy consumption over time should exclude early occupation years as they suffer from occupant adjustment periods. Furthermore, by applying a heat energy factor, none of the dwellings achieve equal or better consumption levels than SAP, however flats and the low consuming group dwellings achieve closest to the predicted.

**Keywords:** assumed heating calculations, actual heating demand, performance gap, Scottish housing, SAP

### Introduction

Heat consumption in domestic buildings is based on thermal comfort and personal hygiene regimes. Both depend on building envelope efficiency, occupant habits and behaviours and heating services. The heating services efficiency is dependent on the Coefficient of Performance (COP), fuel used and the degradation of the system over time, partially affected by poor maintenance patterns. Space heating is dependent on the building's envelope efficiency and the occupant's energy efficient habits. Number of occupants in the dwelling and also the patterns of use in cooking, showering/ bathing can greatly influence fuel used for water heating. Equally significant, are internal gains from latent heat sources, electrical appliances and solar gains influenced by building orientation and fenestration design. Household heat consumption from gas fuel accounts for the majority of the household energy (approx. 80%) and over half of the household's energy bill. (Kane et al., 2011).

Since the Energy Performance of Buildings Directive (EPBD) issued the 2010 guidelines (EU Parliament, 2010) for measurement and verification of energy consumption in buildings, a large focus has been on its calculation methodology, enforcement of minimum energy requirements and the certification process (Burman et al., 2014). In the UK the Standard Assessment Procedure (SAP) is the country's National Calculation Methodology (NCM), producing an Energy Efficient and Environmental Impact score from 1 to 100 (G to A) (Kelly et al., 2012). The SAP scores are based on dwellings heat consumption. The steady state

calculation reflects the predicted performance, however recent studies indicate that actual demand can differ by two and sometimes fourfold (Menezes et al., 2012).

Results from a four year energy monitoring programme categorised by twelve different building suppliers is presented and discussed in this paper. These form part of the wider research project at the Housing Innovation Showcase (HIS) in Dunfermline, Scotland. The statistical study presents initial analysis on the differences between the predicted heat consumption (as calculated by the SAP method) of the dwellings and their delivered heat energy over a four year period. Its aim is to show the importance of longitudinal energy monitoring of buildings for determining the effects of heat energy performance gap. This paper shows the findings after statistically analysing the results using alternative clustering and normalisation methods and alternative means of comparing data. A more detailed explanation of the dwellings and their construction methods can be found in research by Bros-Williamson et al. (2016).

## **Methodology**

The study of this housing development focused on a variety of system providers, all innovative in their fabrication, material use and assembly (off-site or on-site) (Bros-Williamson et al., 2016). A large focus was on comparing delivered heat energy since the dwellings handover in summer 2012 to winter 2016/17 against the predicted results using the SAP. The results are presented by calendar year; year 1 represents the occupied year of 2012 and so on until year 2015 which finalises in 2016. Comparison results have been obtained by taking in-home display (IHD) hourly energy consumption data, corroborated with yearly meter readings, focusing on delivered space and water heating predominantly using natural gas as a fuel.

The yearly delivered energy was analysed statistically to provide more insight into the energy consumption levels, patterns and behaviours of the households. The authors present the statistical data under well-established conventions however new ways of analysing and observing trends have been explored.

The analysis begins by justifying the use of typical grouping and identifier methods. Convention in this area of research selects the use of archetypes of dwellings to obtain groups within the sample. As a result of the small sample size and the varied archetype, it was intended to observe the data differently. The mean (average) delivered heat demand results over the 4 years of monitoring against the heating predicted SAP results are plotted over monitored years, first by archetype followed by consumption grouping converted into Z scores and analysing variables in a K-means cluster analysis (MacQueen, 1967), with one iteration to establish groups. The results effectively divided the sample into three groups; ‘low energy consumer’, ‘medium energy consumer’ and ‘high energy consumer’ relative to the yearly energy delivered within the group.

The paper proceeds to identify the best normalisation factor. Most energy related studies will use delivered energy over a set period, normalised by the heated floor space of the building ( $\text{kWh}/\text{m}^2/\text{yr}$ ). However, in this paper the data is compared by using other conditions such as yearly energy demand per volume ( $\text{kWh}/\text{m}^3$ ), number of people ( $\text{kWh}/\text{ppl}$ ) and predicted over actual energy consumption ( $\text{kWh}/\text{kWh}$ ) (Stinson, 2015). The Coefficient of Variation (CV), as a percentage, was used as an indicator to describe which normalisation condition was a best fit for the data. The lower the percentage CV, the closer each individual data point is to the group mean. This would suggest that the mean is a good representation of the whole data set of that sample.

Following this, the paper proceeds by statistically displaying results with a mixed-design analysis of variance (ANOVA) comparing the significant interaction between archetypes and the three groups K-means method using Z scores during the 4 years of the study.

To conclude, the paper summarises all the methods and compares the predicted against delivered heat energy demand referred to as the heat energy factor (HEF). A HEF of 0 indicates the household consumed equal to its predicted result (SAP), results >0 show higher consumption and <0 show lower consumption than the predicted SAP. The HEF is presented as archetypes (n=4) and consumption levels (n=3).

## Pre-analysis of data

### *Most appropriate identifier*

Four years energy consumption data and many of the household's characteristics have been considered to identify the most appropriate grouping for the sample (n=12).

Typically an archetype classification is used, in this sample there are (n=12), flats (n=2), Bungalow semi-detached (n=2), house semi-detached (n=7) and house mid-terrace (n=1). The flats belong to the denominated four-in-a-block configuration with a separate main entrance.

The mean delivered heat energy and its corresponding mean SAP result by each archetype is plotted per monitored year, shown in Figure 1. The mean SAP results are noticeably lower than any year of the mean delivered heat energy by each archetype ranging from the 3,000kWh/year and 4,500kWh/year. The mean results for each monitored year of consumption are closely grouped. In order to interpret the yearly spread and amount of variability relative to the mean, the CV was calculated. Flats CV = 3%; Bungalow semi-detached CV = 8%; House semi-detached CV = 4%. A CV for the House mid-terrace could not be calculated because of the small sample size. The level of variation within the archetypes is considerably low, signifying it is a good descriptor for the samples energy consumption.

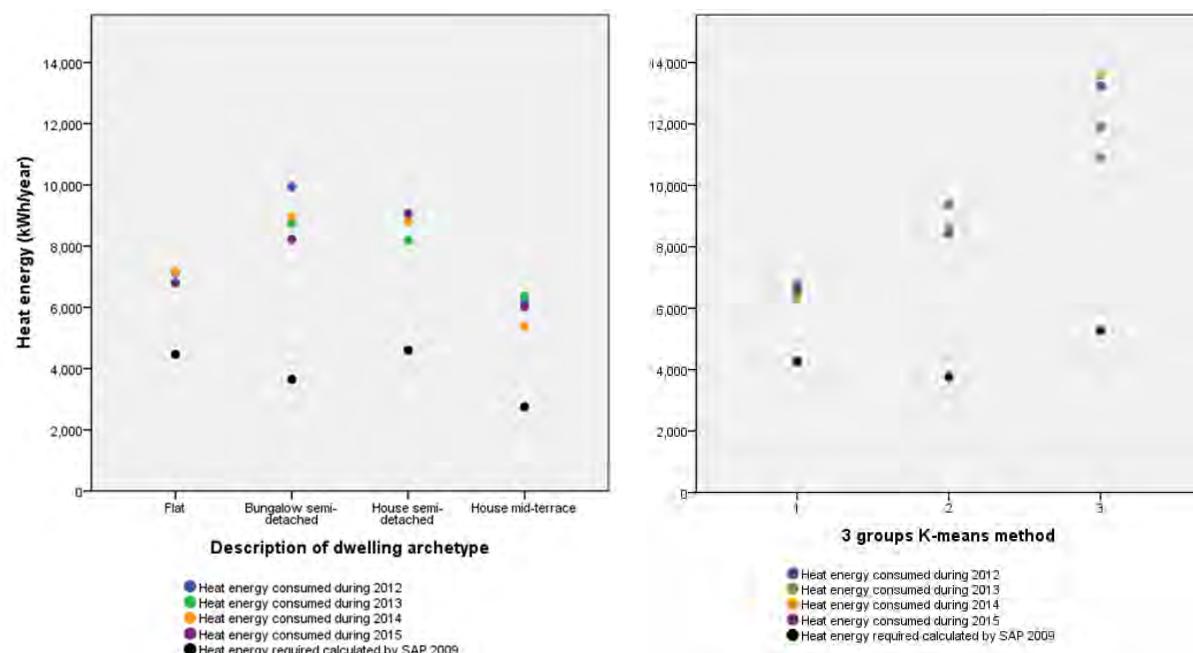


Figure 1. Heat energy by archetype

Figure 2. Heat energy by variables clustering

A second clustering method was applied which considered key variables of the household, including the dwellings floor area, volume, number of occupant adults (>16 years of age), number of occupant children (<16 years of age), the SAP results and the yearly delivered heat energy. This data was converted to Z scores and analysed as variables in a K-means cluster analysis creating the three consumer groups; 1. 'low energy consumer', 2. 'medium energy consumer' and 3. 'high energy consumer'. Figure 2 shows how these compare over the 4 years. The clustering analysis combinations are shown in Table 1 below.

Table 1. Spread of sample group by archetype and variables clustering

Archetypes (n total = 12)	Energy consumer groupings [group]		
	Low [1]	Medium [2]	High [3]
Flats (n=2)	1	1	
Bungalows semi-detached (n=2)		2	
House semi-detached (n=7)	4	1	2
House mid-terrace (n=1)	1		

Analysing the yearly delivered heat energy demand with an on-way ANOVA (analysis of variance) showed that the differences in mean heat energy demand for each archetype was not statistically significant for any of the 4 years ( $p > .05$ ). However, when the sample are split into their associated groups determined by k-means clustering the differences in mean heat energy demand are statistically significant for each individual year ( $p < .05$ ).

Similar to the observed results in Figure 1; the mean results for each monitored year of consumption are closely grouped. Low energy consumer (n=6) CV = 3%; medium energy consumer (n=4) CV = 5%; high energy consumer (n=2) CV = 10%. The level of variation within the group is also considerably low, signifying that identifying the sample by the household's variables i.e. grouping using K-Means method is also a good descriptor for the samples energy consumption. The lower energy consumers are clustered around a mean of 6,500kWh/ year, medium energy consumers mean of 9,000kWh/year whereas the high energy consumers a mean of 12,000kWh/ year.

#### **Most appropriate normalisation factor**

Other authors investigating the performance gap in buildings have conventionally used a normalisation factor of delivered energy for every meter squared of heated floor space ( $m^2$ ).

Table 2. CV values for normalisation factors applied to heat energy

	2012	2013	2014	2015	4 year average
kWh	26%	23%	33%	31%	27%
kWh/m <sup>2</sup>	26%	24%	32%	31%	27%
kWh/ppl	35%	33%	38%	35%	34%
kWh/m <sup>3</sup>	25%	23%	31%	27%	25%
kWh/kWh	33%	33%	33%	35%	32%

Results presented in Table 2 show that by normalising the heat energy consumption data by the volume of insulated space (kWh/m<sup>3</sup>) provided the lowest CV for the sample data. Normalising the heat consumption data by floor area (kWh/m<sup>2</sup>) or energy without normalisation provide the next lowest CV. Normalising the heat energy consumption by number of people (ppl) provided the highest CV, perhaps signifying that the weighting of

people on a 1 to 1 ratio is insufficient to account for the complexities of heat consumption behaviour by households with very young and/or elderly occupants. Normalising the heat energy data by the SAP result (kWh/kWh) returned a high CV value meaning it is not the best for this sample (Stinson, 2015).

## Results

### **Longitudinal comparison of energy demand**

The yearly delivered energy was analysed to provide a clearer understanding of how energy was consumed identifying trends linked to occupant behaviour.

The data in Figure 3 shows that the semi-detached houses, flats and semi-detached bungalows decreased their consumption between year 1 and 2 with a small increase in year 3. The mid-terrace house increases in year 2, then decreases in year 3. The mid-terrace houses increase demand in year 4 meeting demand of year 3 and 4. The heat energy demand profile for the flats is of similar magnitude to that of the house mid-terrace. Also, the profile of the bungalow semi-detached is similar to that of the houses semi-detached.

Results from a mixed-design ANOVA tests suggest that the delivered heat energy levels for each year are similar between the 4 archetypes. These showed that the level of heat consumed over the first 4 years of occupation are not statistically different within the 4 archetypes category  $F(9,24) = 0.608 p>.05$ . Investigating this interaction further, contrasts were performed comparing each year of heat energy consumed to year 1 across the 4 archetypes. These showed non-significant ( $p>.05$ ) differences when comparing the archetypes heat energy consumption for year 2 to year 1  $F(3,8) = 0.472$ . Year 3 to year 1  $F(3,8) = 0.265$ . Year 4 to year 1  $F(3,8) = 1.121$ .

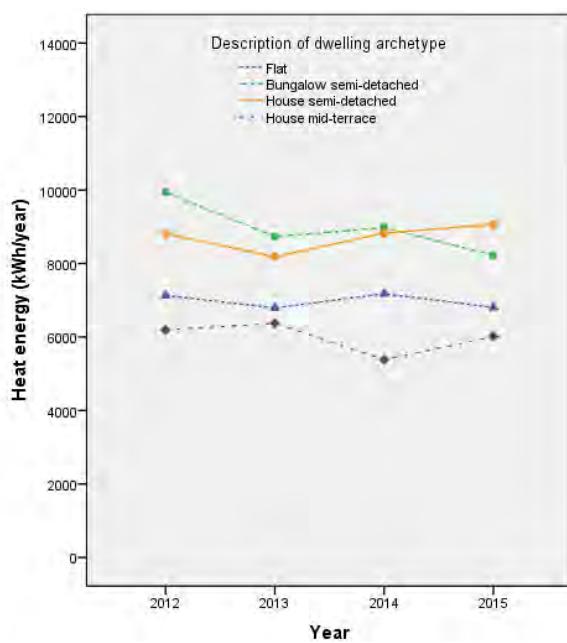


Figure 3. Delivered heat energy by archetype

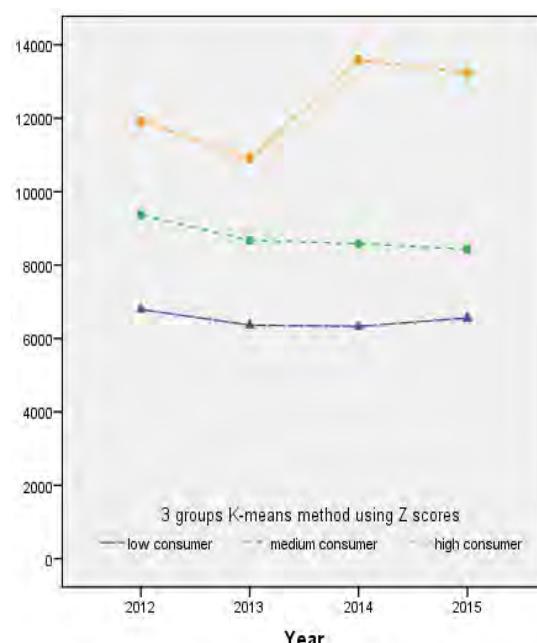


Figure 4. Delivered heat energy between the 3 groups

Figure 4 shows the heat energy demand profiles for each energy level type based on the K-means cluster analysis. The ANOVA results using the heat energy demand as grouped

by the K-means clusters shows that there is a significant ( $p<.05$ ) difference in means over the years and the grouping type,  $F(6,27) = 2.90$ .

Investigating this further, comparing each year of delivered heat energy demand to year 1 across the 3 groups revealed a non-significant ( $p>.05$ ) interaction when comparing the 3 groups delivered heat energy for year 2 to year 1  $F(2,9) = 0.258$ . Year 3 to year 1  $F(2,9) = 3.038$ . Year 4 to year 1  $F(2,9) = 2.255$ . The group of lower and medium heat energy consuming households lowered their heat energy consumption year on year after year 1.

The data presented provides evidence to support the theory that the heat energy demand for year 1 is different from the subsequent years and that yearly heat energy demand data are statistically significant from heat energy consumed in year 1. Dependent paired samples T-test shows the highest consumption was in year 1 ( $M = 8502$ ,  $SE = 634$ ) compared to any of the other of the 3 years (year 2:  $M = 7892$ ,  $SE = 534$ ), (year 3:  $M = 8289$ ,  $SE = 800$ ), (year 4:  $M = 8297$ ,  $se = 752$ ). The difference between year 1 and year 2 delivered heat energy was found to be statistically significant  $t(11)=2.23$ ,  $p<.05$ ,  $r=0.9$ . The differences between other years to the previous year were found not to be statistically significant ( $p>.05$ ).

#### ***Predicted against actual energy demand***

The heat energy factor (HEF) with the sample grouped by archetype is presented in Figure 5 and Figure 6 where the sample is grouped by consumption level. The dashed line indicates a HEF of 0 or the mean SAP score thus less of a performance gap between the groups. The results show that none of the groups align to a HEF of 0 but flats and low energy consumers are the closest. Figure 7 shows all the analysed dwellings delivered heat demand performance is compared against SAP as a percentage above the predicted annual heat energy demand.

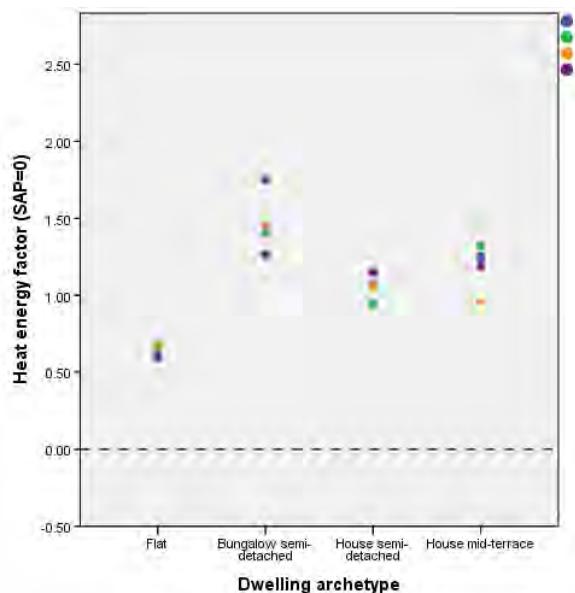


Figure 5. Energy factor by archetype

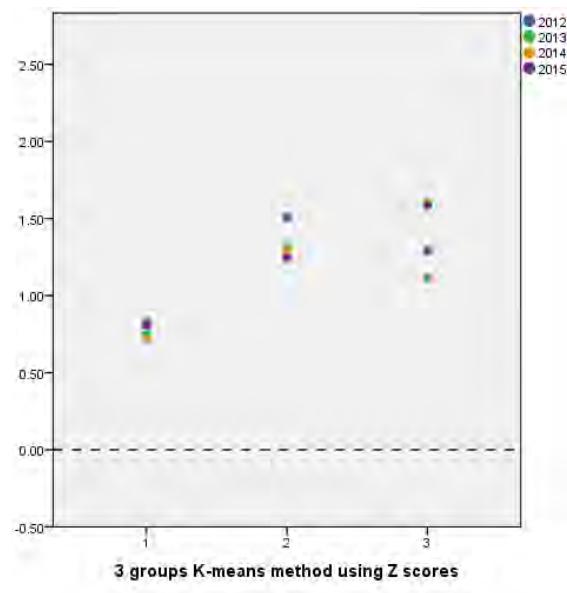


Figure 6. Energy factor by consumption groups

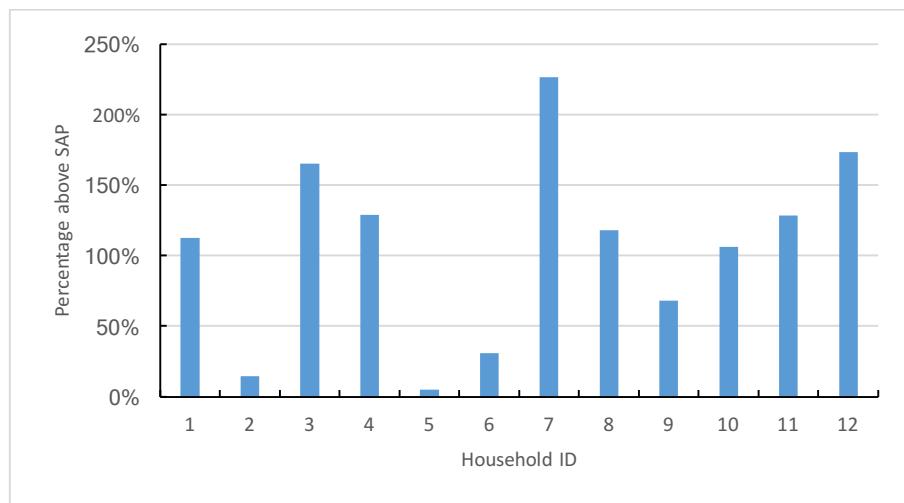


Figure 7. Average of 4 years delivered heat energy compared to SAP

## Conclusion

Using descriptive statistics, this paper investigates the use of conventional and unconventional methods for evidencing the impacts between predicted energy and actual delivered energy of a sample of twelve homes in Dunfermline, Fife.

The conventional use of clustering by archetype has been analysed, as well as proposing a different descriptor of energy demand by grouping low, medium and high energy consumer homes. Both were statistically convenient, however energy groupings evidences the gap in performance clearer over longer periods. In the same way, the normalisation methods used for analysing and benchmarking energy demand. Most will use conventional kWh/m<sup>2</sup>/yr, however this paper uses volume, people and SAP results. Lower confidence of variation (CV) results show that normalising by volume is better than conventional methods.

Finally, results comparing delivered energy over time against the predicted revealed a non-significant ( $p>.05$ ) interaction. This was evident when comparing year 1 against other years, revealing that early occupation years give little evidence of the actual energy consumption with a preference for  $\geq 3$  years of occupation. Furthermore, analysis of the individual household's delivered heat energy showed that the dwelling built with conventional methods and technology, obtained a HEF close to 0 thus performing similarly to the predicted, as shown in Figure 7 as household 5. This observation could lead to concluding that the steady-state compliance tools for predicting energy are better suited to conventional dwellings and possibly not suited to alternative construction types with new technology. It also raises concerns over alternative heating technology, not used suitably by occupants leading to increased energy.

## Acknowledgements

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## References

- Bros-Williamson, J., Garnier, C. & Currie, J.I. (2016) A longitudinal building fabric and energy performance analysis of two homes built to different energy principles. *Energy and Buildings*, 130, pp.578–591.
- Burman, E., Mumovic, D. & Kimpian, J. (2014) Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings. *Energy*, 77,

pp.153–163.

EU Parliament (2010) Directive 2010/30 & 31/EU of the European Parliament and of the Council of 19 May 2010. Official Journal of the European Union - L153, 53 (ISSN 1725-2555), p.40.

Kane, T., Firth, S., Allinson, D., Irvine, K. & Lomas, K. (2011) Understanding occupant heating practices in UK dwellings. In: Energy End-Use Efficiency Issues (EEE) ed. World Renewable Energy Congress 2011. Sweden, pp.8–11.

Kelly, S., Crawford-Brown, D. & Pollitt, M.G. (2012) Building performance evaluation and certification in the UK: Is SAP fit for purpose? *Renewable and Sustainable Energy Reviews*, 16 (9), pp.6861–6878.

MacQueen, J. (1967) Some methods for classification and analysis of multivariate observations. *Proceedings of the Fifth Berkeley Symposium On Mathematical Statistics and Probabilities*, 1 (1), pp.281–296.

Menezes, A.C., Cripps, A., Bouchlaghem, D. & Buswell, R. (2012) Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97, pp.355–364.

Stinson, J.W. (2015) Smart energy monitoring technology to reduce domestic electricity and gas consumption through behaviour change, PhD, Edinburgh Napier University.

UK Parliament (2008) Climate Change Act 2008. London.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainable building design in practice – survey among Danish DGNB consultants

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**Abstract:** Sustainability certification schemes experience growing popularity. Denmark got its own sustainability certification scheme based on the German DGNB certification scheme. Previous work based on four case studies – DGNB certified healthcare centres, suggests further research on how to improve and support the iterative design process in the initial design phases. Therefore, the objective of this paper is to investigate the design process on a more common level experienced by Danish DGNB consultants when designing sustainable buildings using the Danish DGNB certification scheme and thereby possibly verify the findings of previous work, on a more general level. To be able to cover a wide variety of projects and levels of experience with the DGNB scheme, a questionnaire is distributed to Danish DGNB consultants. The survey shows that the design teams to a smaller degree use the DGNB consultant along the design process and particularly so in the early design stages. At the same time, it shows that especially LCA, LCC and acoustical comfort are hardly implemented before the final stages of the design, questioning the holistic nature of the design. The study shows a potential in developing methods and tools to support the initial design phases.

**Keywords:** Sustainability certification, DGNB, survey, design process, decision-making.

### Introduction

Sustainability certification schemes experience growing popularity. In 2010, Green Building Council Denmark (GBC-DK) was founded and Denmark got its own sustainability certification scheme based on the German DGNB certification scheme (GBC-DK, 2016). Investigations of the design processes in four case studies – four Danish DGNB certified healthcare centres, show that the architectural design has been taken too far in the initial design phases without analysing and documenting several DGNB criteria (Brunsgaard, 2016). This questions the quality of sustainability in the overall concept, as it creates a “point of no return”, which means it is not possible to prioritise the assessment points in the certifications scheme when needed. Furthermore, it confirms the importance of multidisciplinary collaboration, including the DGNB consultant, from the early design stages. The study suggests further investigations of the decision-making and design process (DMaDP) on a more common level to possibly verify the findings on a more general level. The research presented in this paper builds upon the previous work.

Nevertheless, why is it important to study design processes? In general, knowledge about the DMaDP is important for us to constantly improve our design approaches and become more efficient. A conventional design process is already highly complex as exemplified by Bryan Lawson:

*"As well as letting in daylight and sunlight and allowing for natural ventilation, the window is also usually required to provide a view while retaining privacy. As an interruption in the external wall the window poses problems of structural stability, heat loss and noise transmission, and is thus arguably one of the most complex of building elements"* ((Lawson, 2006) page 59).

As requirements to energy use and indoor environment tighten due to the recast of the EPBD, EU Member States face new tough challenges moving toward new and retrofitted nearly zero-energy buildings by 2018 and 2020 (European commission, 2014), and due the growing demand for sustainability assessment, the complexity of design process is increasing even further. The general perception is that the "traditional design process" cannot facilitate this complex task. In response, design processes with an integrated design approach that can deal with the higher levels of complexity have been developed, with the aim of ensuring quality in the built environment both technically, functionally and aesthetically (Löhnert et al, 2003; Knudstrup, 2004). Some research shows a tendency for more integrated approaches than earlier, however there is still room for improvement, as demonstrated through case studies of the Comfort Houses (Brunsgaard et al, 2014) and the case study of the Healthcare Centres (Brunsgaard, 2016). We need to become better at handling very complex design processes, and it is important to find out how DGNB comes into play in an already highly complex design process.

The objective therefore is to investigate the DMaDP on a more common level, as Danish DGNB consultants/auditors when designing sustainable buildings using the Danish DGNB certification scheme experience it, and thereby possibly verify the findings of previous work regarding DGNB and design process, on a more general level.

## **Method**

This section will firstly describe the setup of the research design and data collection. Secondly, explain the assessment of the DMaDP. The DGNB consultants and auditors will be named DGNB consultants from here, covering both consultant and auditors as for this study it is not important to distinguish between them.

### **Research design**

The DMaDP is investigated through a questionnaire survey among Danish DGNB consultants. A questionnaire survey is a suitable approach for this research, as it is possible to investigate the topic among a large number of respondents and thereby cover a wide variety of projects and levels of experience with the DGNB assessment scheme (Bryman, 2004; Johansen & Friis, 2011). The questionnaire is distributed to 324 Danish DGNB consultants, who are considered a representative sample for this study. However, the size of the sample is too little to generalise, therefore conclusions will be indications or tendencies of the experiences with DMaDP using DGNB certification schemes. The questionnaire is prepared in the software SurveyXact (Rambøll Management Consulting, 2017) and distributed by email containing an invitation to participate in the survey and a brief introduction to the theme and aim of the questionnaire. GBC-DK provided the email addresses, and the consultants have answered the questionnaire online. The respondents are promised anonymity. A reminder was sent to consultants who have not answered to collect more answers. Following topics are covered in the questionnaire: Level of experience with DGNB in general, experience with the DMaDP in relation to stakeholders involved in different phases, documentation process and time consumption. Especially questions regarding the documentation process are important as

they indicate to what extent specific topics are considered, particularly in the early design stages where the main architectural concept is established. Not all criteria from the DGNB assessment scheme are covered in the questionnaire for these reasons: Firstly, to minimise the time consumption for answering the questionnaire. Secondly, to focus on criteria especially linked to the architectural form concept and expression. Those topics are: lifecycle assessment (LCA), lifecycle cost assessment (LCC), energy use, thermal and atmospheric comfort, visual comfort (daylight) and building integrated art. Some questions refer to phases of the design process, which are used when determining periods for documenting the selected topics in the process and when different actors are involved. The five phases are described in Table 1. When answering the questionnaire, the consultants are asked to base their answers on the latest project they have certified, again to minimise the time consumption for filling out the questionnaire.

Table 1. Description of the five phases of the design and construction phase used in the questionnaire

Idea and analysis phase	Concept and sketching phase	Synthesis phase	Project design phase	Construction phase
Analyses are carried out and design parameters are defined, i.e. decisions about the project's scope, functionality, quality, indoor environment, aesthetics, time and finances.	Developing the first ideas and concepts for the project. It will end with a clear concept and the first concrete design solutions.	The project is beginning to find its final form. The design reaches a stage where all design parameters "fall into place", as a whole.	The details in the projects are specified. The outcome will create regulatory approval of the final documents and completion of the building.	The building is constructed.

### **Assessing the DMaDP**

In order to reach high-performance and high-quality design of buildings, the complex design processes are ideally analogous to an integrated design approach. Therefore, the fundament to assess the DMaDP takes its point of departure in approaches to the Integrated Design Process (IDP) – One approach developed by International Energy Agency, Task 23 (Löhnert et al, 2003) and a similar approach developed by Mary-Ann Knudstrup, Aalborg University (Knudstrup, 2004). The key elements of the approaches, which are used when assessing the DMaDP, are iterative process, involvements of actors and documentation of important topics. The involvement of all relevant actors from the beginning of the project bringing in necessary knowledge and competences earlier than in a “traditional design process”, typically engineering knowledge, but also specialist knowledge, and in this case knowledge from the DGNB consultant. Bringing in competences timely allows additional test of constraints in the early design stages, resulting in a holistic concept and minimizing the risk of repair-work later in the design process, which usually has drawbacks for both the economy and quality of the design. Therefore, the questionnaire asks in which phases different actors are involved. By bringing together the different actors earlier, the principle is to evaluate the design continuously in loops of iterations throughout the process regarding technical, functional and aesthetic issues. The evaluation is supported by calculations/ simulations of e.g. energy use and indoor environment throughout the design process. Therefore, the questionnaire asks when selected topics are documented to clarify the level of knowledge on which the decisions are made.

## Results

The response rates of the 324 distributed questionnaires are presented in Table 2. The final response rate is 18%; therefore, the conclusions will be tentative. On the other hand, approximately 40 buildings have been certified in Denmark at the time of writing and adding up the answers regarding the amount of DGNB certified projects the consultants have completed, the numbers match. Therefore, a higher response rate will not change the result significantly, as the remaining consultants must be without experience in completing a DGNB assessment.

Table 2. Fact box of the survey

Size of sample	324
Response rate (completed the questionnaire)	58 (18%)
Response rate (partly completed the questionnaire)	21 (6 %)

### ***Level of Experience with DGNB Projects***

The level of experience is categorised in three groups, as presented in Table 3: The first group has used DGNB assessment and completed one or more certifications; the second group has used DGNB assessment without completing a certification and the third group has no experience with DGNB assessment. This paper will focus on the first group. However, it is interesting to see that the main reasons for not having completed or not having any experience in using DGNB primarily are founded in lack of DGNB assignments. Secondly, it is related to certification cost and documentation workload, which possibly have resulted in the first reason – lack of DGNB assignments. Cost and time resources are tough arguments and can become the decisive argument for the client to deselect a certified sustainable building. Another interesting discovery is that several consultants have experience with more than one project. It might show that by having experience with completing a DGNB assessment once, you are more likely to be hired to do an assessment again.

Table 3. Level of experience with DGNB projects and reasons for not using DGNB certification. The sums will not add up 100%, as respondents can be in both group 1 and 2 and are allowed to give more reasons.

Category of use	Number of respondents	Number of projects	Main reasons for not using/completing DGNB certification
<b>1) Used DGNB and completed a certification</b>	26 (45%)	14 consultants have completed more than one certification	
<b>2) Used DGNB without completing a certification</b>	24 (53%)	24 consultants have used the certification scheme more than once	<ul style="list-style-type: none"><li>- The client did not ask for DGNB certification (56%)</li><li>- Too high certification cost (31%)</li><li>- Certification was dropped (25%)</li><li>- The documentation workload was too high (19%)</li></ul>
<b>3) No experience</b>	13 (22%)		<ul style="list-style-type: none"><li>- Not yet been hired on project as consultant (54%)</li><li>- Educated consultant for other purposes than certification e.g. teaching or research (31%)</li></ul>

### ***Involvement of Actors***

The following results are based on answers from respondents in group 1. As described earlier, involving relevant stakeholders from the beginning of the project allows competences to be integrated earlier than in a conventional process. The respondents were asked to answer to

what extent each actor was involved in each phase of the design process; the outcome is shown in Table 4. Not surprisingly, the architect is highly involved throughout the whole design process, whereas the constructing architect and the contractor are mostly involved in the project design phase. The engineer has been involved in all phases parallel to the architect, only with a reduced amount of involvement. It indicates that the engineer has been involved to some extent in the early design stages, contributing with engineering competences in the decision-making – interpreted to be more than in a “traditional design process”. What should be noted is how little the DGNB consultant is involved especially in the early concept/sketching phase, where the main form concept is found and in the synthesis phase, where the project finds its final form. In those two phases, the design team will make decisions that will limit “space of solutions” for the next design phase and reach “points of no return” after which the possibility to prioritize the assessment criteria linked to the architectural form is limited. Leaving out the DGNB consultant in the early design phases requires that the rest of the design team has been well informed by the consultant, concerning where to go with the design. It is questionable if the projects have been tested well enough against DGNB requirements in the early design stages. This study cannot tell if the lesser involvement of the DGNB consultant in the early design phases has resulted in repair-work later in the design process, or if it had drawbacks for the economy and quality of the design, however that could be the outcome risk. Another interesting finding is how relatively much the DGNB consultants have been involved in the project design phase, where the building design is fixed. It may well reveal that the assessment primarily is done as a documenting step and not as an informing step in the design process.

### ***Documentation process***

The decision-making is ideally supported by evaluation and/or documentation of key topics of the assessment scheme to estimate whether the design is moving in the right direction or not. Table 5 shows how the respondents estimate the documentation of the different topics in the different phases; they can select more phases to each topic. The greener, the earlier the topic has been evaluated. LCA and LCC are only to a little extent documented in the early phases, instead more than 35% answer that LCA and LCC are documented in the construction phase, where the whole design is completed. Equally, approximately 35% also answer that LCA and LCC are documented in the project design phase, where the design is more or less fixed, however, a few elements like materials are still possible to change. This means that the concept is not fully holistic in its nature and potentials for optimisation concerning both points in DGNB assessment and the architectural qualities can be missed. Choice of materials is highly linked with the architectural qualities as regards aesthetics and perception, but also linked with the building's physical performance. Topics like energy use, thermal comfort and daylight are well documented in all phases, with a little overweight in the project design phase. Especially energy use has increasingly become a common part of the design process, as the building regulations regarding energy use have been continuously tightened every fifth year in Denmark and will be again in 2020. Compared to studies of design processes in a Danish context done a few years ago (Brunsgaard et al, 2014), the thermal comfort in these cases has been documented quite well in the earlier design stages, showing that the awareness and importance of thermal comfort has matured in the building industry. Additionally, the indoor environmental requirements have recently (July 2016) been included in the current building regulations, which means the design team now must document the indoor environment to get building permission.

Table 4. Level of involvement of each actor in each phase. The colours in the pie chart equal level of involvement and the size of the slice equals percentage of responses.

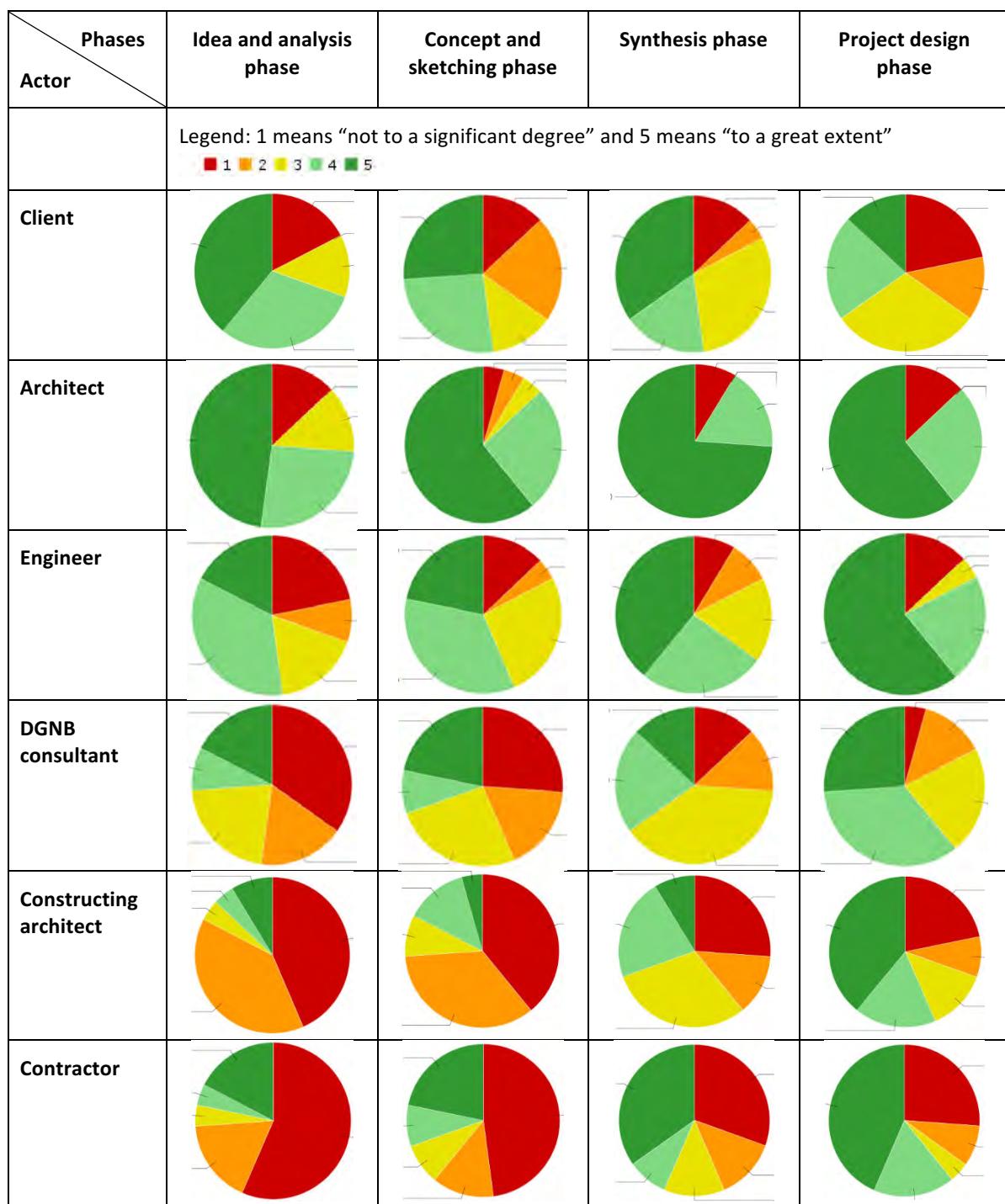
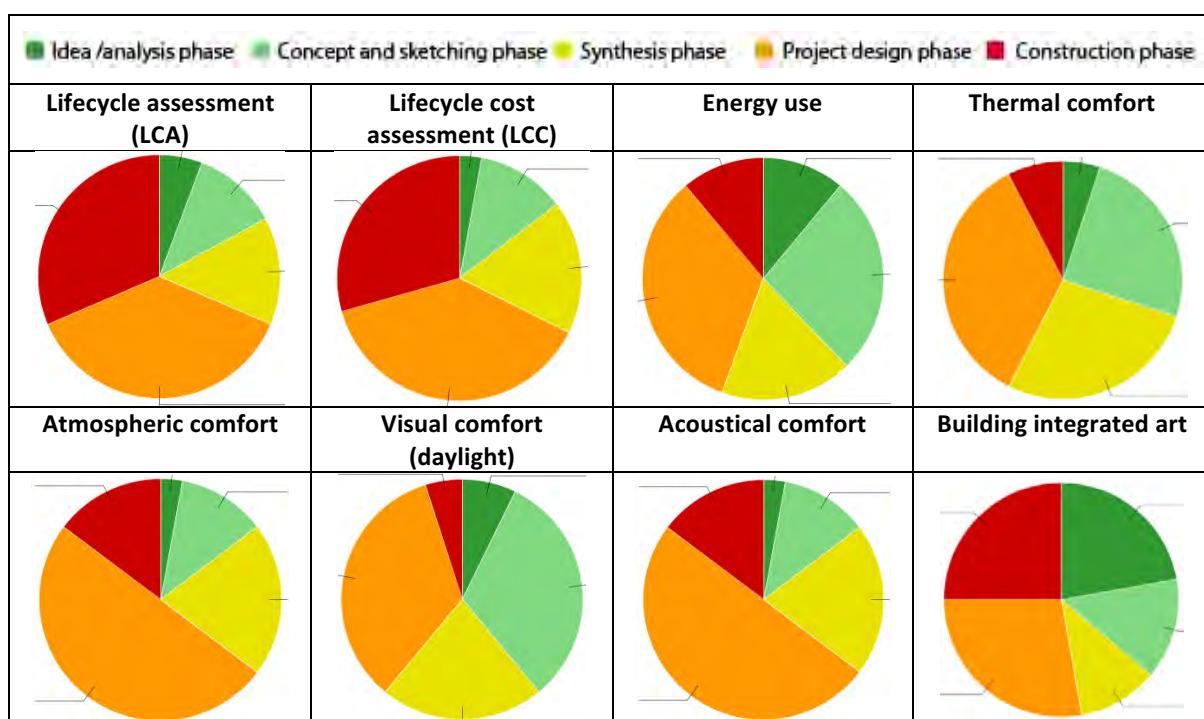


Table 5. Documentation of topics in the different phases. The colours in the pie chart equal the phases and the size of the slice show how much the topic has been documented.



To support the above findings, the consultants were asked to answer which of the topics they found the hardest and easiest to implement in the concept and sketching phase. The top three most difficult topics in prioritised order are LCA, LCC and acoustical comfort, whereas the easiest to implement are energy use, visual and thermal comfort. These answers also fit with Table 5. Concerning time consumption, 12 out of 14 consultants answer that they use "more" or "significantly more" time in a DGNB project compared to a similar project not assessed by DGNB.

#### ***Consultants' suggestions for improvement opportunities***

Nine consultants wrote suggestions to improve the DMaDP. Six of them would like to simplify the process especially in relation to LCA and to some extent LCC. Some suggested light versions of LCA and LCC tools and others suggest implementation in BIM. Another comment was that DGNB assessment is best suited for documenting the final project and difficult to handle in the initial phases informing the design process.

#### **Discussion**

Even though the DGNB consultants are considered a representative sample for this study, an inclusion of other actors of the design process, like the architect and the engineer, might have changed the outcome of the result as they could have experienced the process differently. Because the DGNB consultant evaluates his/her involvement as fairly minor in the initial phases, it is questionable if he/she can answer to what level the different actors have been involved and when different topics have been documented. Some processes might have been running between the architect and engineer without the DGNB consultant's awareness. However, it is expected that the consultants have the overview of the different criteria in the assessment scheme. They are asked to answer according to recent projects they have certified, however that limits the amount of processes covered by the questionnaire. To

compensate, they are asked whether the project represents previous process(es) or not. Their responses are equally on each side of neutral.

## Conclusion

The survey shows that to a smaller degree, the design team uses the DGNB consultant along the design process and particularly so in the early design stages. At the same time, it shows that especially LCA, LCC, acoustical and atmospheric comfort are not very implemented before the final stages of the design. This means that the concept is not fully holistic in its nature, and potentials for optimisation both regards to points in DGNB assessment and the architectural qualities can be missed. Furthermore, the consultants find those topics hard to implement in the early design stages. The study shows a potential in developing methodologies and tools to support the initial design phases securing an iterative DMaDP based on a sufficient level of knowledge, covering topics relevant to the architectural design, or at least the topics hardest to implement.

This study will be further developed as 13 respondents volunteered to be contacted afterwards for a telephone interview. It will allow the findings to be further unfolded and explained e.g. has there been any repair work to the design in later stages and why. Additionally, it would give more answers to what kind of support the design teams would like to have to improve or develop the DMaDP, in the initial stages.

## References

- Brunsgaard, C, (2016). Sustainability Certification (DGNB) and Design Process in the Case of four Healthcare Centres. In *CLIMA 2016 - proceedings of the 12th REHVA World Congress*. Aalborg University 2016
- Brunsgaard, C. et al. (2014). The Critical Design Process: Experience from some of the First Passive Houses in Denmark. *Journal of Architectural and Planning Research*, 31(2), pp.163–180.
- Bryman, A. (2004). *Social Research Methods*. Social Research, 2nd, Oxford: Oxford University Press.
- European commission (2014), European commission 2014 - Making buildings more sustainable to improve health and comfort. Available at: [http://ec.europa.eu/research/infocentre/article\\_en.cfm?artid=32084](http://ec.europa.eu/research/infocentre/article_en.cfm?artid=32084) [Accessed February 2, 2016].
- GBC-DK (2016), Green Building Council Denmark. Available at: <http://www.dk-gbc.dk/> [Accessed January 25, 2016].
- Johansen, K.R. & Friis, L. (2011). *En ny undersøgelse viser - eller gør den?: en praktisk guide til spørgeskemaundersøgelser*, Århus : Ajour.
- Knudstrup, M.-A. (2004). Integrated Design Process in Problem-based learning. In *The Aalborg PBL Model: Progress, Diversity and Challenges*. Aalborg: Aalborg Universitetsforlag. pp. 221–234.
- Lawson, B. (2006). *How Designers Think: The Design Process Demystified*, London: London Architectural press
- Löhnert, G. et al. (2003). *Integrated Design Process: A guideline for sustainable and solar-optimised building design*, Task 23 Optimization of Solar Energy Use in Large Buildings Subtask B, International Energy Agency
- Rambøll Management Consulting, SurveyXact. Available at: <http://www.surveyxact.dk/> [Accessed March 25, 2017].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Green School Design – Key Strategies in Tropical Developing Regions

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**Abstract:** The green school movement has been developed in Western countries, such as America, England, and Australia, for decades. “whole-school sustainability” has been defined and developed as a core value and solid foundation of the green school design framework worldwide. In tropical developing regions, scarce resources and limited budget become barriers to promoting green schools and education of sustainability. Even so, there are pioneer green schools from these regions which apply technologies with low costs and simple maintenance to achieve whole-school sustainability in rural areas. These pioneer schools had awarded from international green school programs for their significant efforts. In those reward programs, schools are measured by the criteria set for developed countries. However, the contributions of these pioneer green schools go beyond the framework of the measurement. This paper introduces two green school pioneers from these regions, based on the requirements of the LEED V4 for Schools rating system, which has been used as the worldwide measurement in the award program “The Greenest School on Earth.” Beyond the basic requirements, these two schools provide solutions for environmental problems, such as water scarcity, disposing of human excreta, and waste treatment. These additional solutions represent how a green school can solve essential problems in these regions, and, most importantly, how they turn these solutions into teaching tools, to enhance environmental awareness for students, teachers, and communities. This review of the key design strategies of green schools demonstrates the most feasible solutions for tropical arid climates, to encourage authorities and educators to convert their teaching environments into green campuses.

**Keywords:** Green School, Key Design Strategies, Tropical Developing Regions

### Introduction

According to State of the Tropics (2012), by 2050, more than half of the world population will live in tropical regions, with 67% of children under 15 years old. Most tropical countries are developing countries, and will remain the same in the 21st century. Furthermore, tropical regions will play a vital role in sustainable development due to their rapidly growing economies and population (State of the Tropics, 2012). From “A World at School,” there are crucial barriers to education in developing regions, apart from critical issues of society, culture, and finance (Watt, 2014), “Lack of school buildings,” “travel distance from home,” and “poor sanitation facilities” are crucial issues in this situation (Global Citizen, 2014; Watt, 2014). In these regions, school facilities become critical and a priority for education development.

The green school movement has been developing globally over the past 40 years, since environment education (EE) was defined by UNESCO (The United Nations Educational, Scientific and Cultural Organization) in 1977 (UNESCO, 1978). However, in tropical developing regions, the green school movement is far less developed than in Western countries, despite the significant achievements of pioneer green schools from these regions, both in sustainable learning environments and education for sustainability, as well as their connection with local

communities. Two schools in this research have received a “The Greenest School on Earth” award. In this international awarding program, schools from all over the world are measured under the same criteria: LEED (Leadership in Energy and Environmental Design) V4 for Schools.

Whole-school sustainability of green schools has been highlighted by Rachel Gutter, director of the Centre for Green Schools (CGS), authority on the Greenest School on Earth program. Whole-school sustainability engages students in every aspect of sustainability, from their learning of knowledge and behaviour in daily life, through practicing in the school environment, the most important thing is to cultivate students to be global green leaders in improving the environment (Peterson, 2015). The definition of green schools follows the themes and criteria of LEED V4 for schools. Themes include: location and transportation, sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environment quality, innovation in design, and regional priority. Five major themes make up 75% of the credit in this rating system (Table 1). Each of these five themes has always required items which become the baseline for certification as a green school (LEED V4, 2016)

Table 1: Five Major Themes Basic Requirements from LEED, Data from (LEED V4, 2016)

Themes	Always Required Items
Sustainable Site	• Construction activity pollution prevention; • Environmental site assessment
Water Efficiency	• Water use reduction; • Indoor Water use reduction; • Building-level water metering
Energy and Atmosphere	• Fundamental commissioning and verification; • Minimum energy performance • Building-level Energy metering; • Fundamental refrigerant management
Materials and Resources	• Storage and collection of recyclables; • Construction and demolition waste management planning
Indoor Environment	• Minimum indoor air quality performance; • Environmental tobacco smoke control • Minimum acoustical performance

## Methodology

In this research, design strategies of two pioneer schools from tropical developing regions will be presented in five major themes from LEED V4 for Schools within the “always required” content. The rating system from LEED presents basic requirements for green schools worldwide, it also represents the most up-to-date design strategies in the Greenest School on Earth program. This research will illustrate the achievements of two green schools, and discover their effective and feasible solutions beyond LEED basic requirements.

## Cade Study

Two green schools from Asia and South Africa have received the Greenest School on Earth awards. Bali Green School was the winner in 2012, while Vele Secondary School received an honourable mention in 2014 (CGS, 2012; Cowan, 2015).

Table 2 Brief Introduction of Bali Green School and Vele Secondary School

	Bali Green School (2008 built)	Vele Secondary School (2011 built)
Location	 Figure 1: Bali Green School in Tropics' Map	 Figure 2: Vele School in Tropics' Map

<p><b>Figure 3: Climate Data of Bali-Tropical</b></p>	<p><b>Figure 4: Climate Data of Mavhuwa-Subtropical</b></p>
<p><b>Figure 5: Wind Rose of Bali</b></p>	Wind is from SSE to NNW, Stable direction at 157.50°
<p><b>Figure 6: Wind Rose of Marhuwa</b></p>	Wind is from SE to NW, Stable wind direction between 112.5° - 135°
Student Classroom Site Area Cost	400 Students 10 buildings for separated classrooms 103,142.63 m² / Building Area: 7,542 m² \$3,116,318 US in total \$375 US Per sqm
460 Students 17 classrooms in 3 buildings 51,344.16 m² / Building Area: 3,700 m² \$725,000 US in total, \$200 US Per sqm, facilities are partly donated	

Data from (Creating Schools, 2017; Meteoblue, n.d.a; Meteoblue, n.d.b; Shim, 2010)

These schools represent up-to-date strategies for green schools in tropical developing rural areas. They were chosen also because both campuses include classroom buildings, a library, sports fields, and a range of student ages, which will demonstrate more solutions.

### Sustainable Site – Construction and Eco-system protection

- Construction activity pollution prevention; • Environmental site assessment

Sustainable site requirements are related to construction activity pollution and assessment of site contamination. In both schools, the requirements are easily to achieve with the use of local materials and traditional building skills. With the contribution of school plantation gardens and green spaces, the campuses are able to avoid site contamination, both in the construction process and operation. (Table 3; Table 6)

### School Food Plantation and Gardens

In Bali Green School, school gardens are located separately and become connections between different buildings. There is a cocoa plantation, organic gardens, a medicinal garden, and peace garden; combined with green paths, the campus is filled with green learning spaces (Shim, 2010, p. 5). In Vele School, the food plantation uses rainwater for irrigation and provides organic food for the school kitchen. This effort produces a secure supply of healthy food, and plays an educational role in the organic plantation. The other achievement at Vele School is the green roof which covers walkways and part of the building's roof; this green belt provides shade for outdoor with local indigenous flora. (Table 3) (Creating Schools, 2017)

### Sanitation and Waste Treatment

The eco-toilets at Bali Green School apply a predominantly aerobic process to treat human and animal excreta. The compost station, where biomass, kitchen waste, and cow manure are collected and composted, creates organic fertilizer for the gardens and plantations. This green nitrogen mix is combined with brown carbon layers composed of wood chips, brown leaves, food scraps, and manure (Shim, 2010). In Vele School, bathrooms are surrounded by the plantation, covered with a green roof, and located in the centre of campus. The toilet uses a

waterless and on-site dry sanitation system called “Enviroloo.” The waste from the dry toilet goes to septic tanks and produces bio-gas for cooking (Creating Schools, 2012).

Food plantations and waste treatment systems in both schools act as green yards, organic food suppliers, and learning spaces for demonstrating botany, biology and cultivation knowledge. Sanitation systems use biotech approaches to transform waste into useful resources and minimize the risk of pollution. Both of their design strategies are not included in the requirements of land protection from the LEED system; however, they all play vital roles in protecting the local eco-system and community habitat.

Table 3 Sustainable site, plantation, and eco-toilet design strategies comparison



Figure 7 Bali School Campus

Figure 8 Bali School Plantation

Figure 9 Bali Green Eco-Toilet

Bali Green School Sustainable Site (Photos by Author)



Figure 10 Vele School Campus

Figure 11: Vele School Plantation

Figure 12: Vele School Dry Toilet

Vele School Sustainable Site (Photos copyright permitted by Architect Steve Kinsler - Creating Schools)

### **Water Efficiency**

- Water use reduction; • Indoor Water use reduction; • Building-level water metering

In the LEED system, water-use reduction and metering are prior requirements for green school certification. In both schools, water-use reduction is a priority on campus. Basic metering systems have been used to monitor the use of water. Due to the scarce rainfall during the dry season in these regions, water resources are critical; however, rainwater collection and waste-water recycling are not included in the LEED system. The use of rainwater and used water could play a vital role in solving water scarcity problems.

Table 4: Water Resource and Consumption, Data from (Shim, 2010; Yong, 2010; Creating Schools, 2017)

	Bali Green School			Vele Secondary School		
Water Resources	60-meter well	River and well	River	Rainwater		Underground water
Collection	Solar energy pump from well	Pump	Pump	From classroom blocks, ground surfaces, roof, solar energy pump	From school hall roof	Solar energy pump from underground
Storage	No Storage	No Storage	No Storage	Store in 100,000-litre tanks, pump to 20,000 litre header tanks	30,000-litre tanks	10,000-litre elevated tanks
Use areas	Drinking Water	Non-potable Water	Fire hose	Irrigating food gardens	Irrigating sports field	Kitchen, drinking, and wash basins

Metering	RO filtering / metering	No	No	Yes	Yes	Yes
Water Recycle	Waste water from kitchen and bathroom are used for garden watering.			Water flows from kitchen, waterless taps, and toilet will be collected in septic tanks and be digested into bio-gas, slush will be sent into earth via French drain.		

In Bali Green School, drinking water comes from a 60-metre deep well, water for other uses is pumped from the river. Grey water is simply collected from the kitchen or bathroom and reused to water gardens. There is no evidence that a water management system has been used to control the use of water and wastewater treatments. (Yong, 2010; Shim, 2010)

The low-cost and simple maintenance rainwater management system is the most significant effort at Vele School. Except for drinking water, which is pumped from underground, all water is supplied by rainwater. Vele School has an effective rainwater harvesting and storage system. It reduces water use and recycles grey water to achieve water efficiency via its irrigation system, waterless toilet, and water-saving taps, etc. (Creating Schools, 2017)

### ***Energy and Atmosphere***

- Fundamental commissioning and verification;
- Minimum energy performance
- Building-level Energy metering;
- Fundamental refrigerant management

Due to the local climate conditions and low passive-design strategies in both campuses, no cooling or heating system has been used in either school, so refrigerant-related issues have been avoided. Energy performance has been set as a priority on both campuses. Solar panels are the main power resource, and basic metering systems are used to monitor the energy performance on both campuses. (Table 5)

Bali Green School installed a solar PV system on 2011. This system comprises 108 solar panels which have been mounted on bamboo structures for a flexible installation. A 72kWh capacity battery bank and inverter store all energy generated from solar. This system provides 21 kWp for school use (Akuo Foundation, 2013). The campus locates in riverside, and a micro-hydro vortex was built in earlier years; in 2016, it provides approximately 6 kWh. Bali Green School has become energy self-sufficient from these efforts (Green School, n.d.)

In Vele School, energy resources come from two sources: the public power grid and solar power. The solar panel installation also includes a metering system for monitoring energy consumption. However, only computers and the water pump use the power from solar energy, other electrical operations still rely on the public power grid. (Creating Schools, 2017)

Table 5 Energy Resource and Consumption, Data from (Akuo Foundation, 2013; PJCarew Consulting, 2011)

	Energy Resource	Quantity	Capacity	Use in Facilities	Monitor& Metering	Self-sufficient
Bali Green School	Solar PV	108 Panels	21 kWp	All electrical facilities in campus	Yes	Yes
	Hydro Vortex	1	6 kW			
Vele Secondary School	Solar PV	50 m <sup>2</sup>	6.4 kWp	100 Computers & Water Pumping	Yes	No (< 50%)
	Eskom public grid			Lighting / electrical		

### ***Materials and Resources***

- Storage and collection of recyclables;
- Construction and demolition waste management planning

The basic requirements of LEED emphasise the use of recyclable and waste materials, especially in storage and management. But the use of local and renewable materials which are inspired by local traditional building skills are the most significant effort on both campuses, although they are not included in the basic requirements.

In Bali School, bamboo, as a recyclable building material, has been used for structures, flooring, furniture, and most facilities; even the sawdust of bamboo has been used to boil hot water and for cooking in the kitchen. Proper treatment will enhance bamboo's resistance to humidity, insects, and mould. The life-cycle of bamboo in building is 20 years, and it only takes 4-5 years to grow to a suitable size for construction. Using traditional Balinese building skills, the roof consists of thatch, using coconut or palm tree leaves, alang alang grass, and rice straw. The ground floor uses local mud mixed with 15% cement for flooring (Shim, 2010).

In Vele School, old school buildings are retained and restored, materials were given back to the community to use. New buildings use a combination of construction with local materials such as kiln-fired clay bricks, wood, light steel, concrete, and local stone. Reduction of waste in material use has become a management priority on site. Any possible materials for construction have been specified and resulting into site works like flooring filling and retaining structure in this project. (Lafargeholcim Foundation, 2013)

Table 6 Building Materials and Resource Comparison



Figure 13: Furniture



Figure 14: Alang Alang Roof



Figure 15: Structure



Figure 16: Indoor Sport

Bali Green School (photos by Author, 2015)



Figure 17: Corridor



Figure 18: Dry Toilet



Figure 19: Student Hall



Figure 20: Classroom

Vele Secondary School (Photos copyright permitted by Architect Steve Kinsler - Creating Schools)

### **Indoor Environment**

- Minimum indoor air quality performance; • Environmental tobacco smoke control
- Minimum acoustical performance

Air quality performance is measured via the ventilation rate; in these two green schools, natural ventilation can be ensured by the semi-outdoor classroom and building orientation with openings (Figure 21; Figure 22). Bali School has a unique solution to managing acoustic performance, with the semi-outdoor classroom which has individual spaces surrounded by plants and trees which provide natural layers of insulation. In Vele School, kiln-fired clay bricks formed medium weight wall which provide effective layer of acoustic insulation.

Low passive design in both campuses has benefits beyond these requirements. In Bali School, classrooms have different shapes, skylight forms built with bamboo and canvas bring indirect light which reduces heat and glare (IBUKU, 2012). The classroom with no walls design has become a semi-outdoor space which brings fresh air for natural ventilation. In Vele School, natural light comes from north-facing windows, with a small roof overhang to reduce the heat. The chalkboard is installed on the south wall, and sunlight comes from behind the seats which reduces cross shadows on the desks. Windows and doors, open to the south corridor, also bring skylight from the corridor's metal roof (Creating Schools, 2012, p. 14)

Table 7: Typical Classroom Measurement Comparison, Data from (IBUKU, 2012; Creating Schools, 2012)

Themes	Bali Green School Classrooms	Vele Secondary School Classrooms
Shape	Ellipse floor, "turtle-shell" roof	Square with wooden roof frame
Dimensions	$\approx 18\text{m} \times 10\text{m} \times (\text{H } 4.5\text{m} \sim 7.5\text{m})$	$\approx 7\text{m} \times 7\text{m} \times (\text{H } 3.0\text{m} \sim 4.5\text{m})$
Shading	$\approx 3.5\text{m}$ (Overhanging roof)	$<0.5\text{m}$ (Shading device)
Orientation	optimal north facing	optimal north facing
Ventilation	Semi-Outdoor design brings natural ventilation, wind is from Southern South-East to Northern North-West	Windows on north and doors on south corridor provide natural ventilation, wind is from South East to North West.
Light	Canvas on roof ridge provide skylight	Indirect sunlight from shading device; skylight from metal roof.
Insulation	No	Roof Insulation

Figure 21: Turtle Classroom Section Diagram

Figure 22: Classroom Section Diagram

### Discussion and Finding

Both schools have significant achievements in the five major themes of the LEED V4 for Schools rating system. With costs of construction around \$200 USD to \$375 USD per m<sup>2</sup> (Table 2), these two pioneer schools have proven their ability to achieve high performance in sustainable land, water efficiency, energy, application of local building materials, and indoor environment, which are the basic requirements of the LEED V4 for Schools rating system.

Beyond the framework of this rating system, the rainwater collection and waste water recycling system at Vele School demonstrates the most feasible water solutions for tropical arid regions. This water system has become a model for educating students and communities about water conservation in areas of water scarcity. School gardens and food plantations are more than green spaces in protection campus environment, these spaces also provide organic-plantation learning spaces. Eco-toilet systems in both campuses represent achievable solutions for sanitation problems. Moreover, these design strategies are used as educative tools, while, at the same time, making significant improvements to the school environment.

### Conclusion

From this review, pioneer green schools in tropical developing regions demonstrate a low-tech and low-cost model for achieving green school certification. Beyond the requirements, the two schools provide solutions in dealing with local resources, which make a vital contribution in local sustainability.

Design strategies summarised from these pioneer schools demonstrate the most achievable approaches in these regions; the rating system should be upgraded according to the practices to be a design guide for new schools in these regions.

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## Reference

- Akuo Foundation, 2013. Green School in Bali. [Online] Available at: <http://www.akuofoundation.com/en/projects/green-school-in-bali.html> [Accessed 18 March 2017].
- CGS, 2012. The 2012 Greenest School on Earth: Green School Bali. [Online] Available at: <http://www.usgbc.org/articles/2012-greenest-school-earth-green-school-bali> [Accessed 14 March 2017].
- Cowan, C., 2015. The Greenest School on Earth: How do you choose?. [Online] Available at: <http://www.usgbc.org/articles/greenest-school-earth-how-do-you-choose> [Accessed 14 March 2017].
- Creating Schools, 2012. Vele Secondary School : Limpopo. [Online] Available at: <http://creatingschools.co.za/VELE-HIGH-SCHOOL.pdf> [Accessed 10 March 2017].
- Creating Schools, 2017. Vele Secondary School. [Online] Available at: [http://creatingschools.co.za/?page\\_id=33](http://creatingschools.co.za/?page_id=33) [Accessed 18 March 2017].
- Global Citizen, 2014. 10 barriers to education around the world. [Online] Available at: <https://www.globalcitizen.org/en/content/10-barriers-to-education-around-the-world-2/> [Accessed 20 March 2017].
- Green School, n.d.. Learning Environment. [Online] Available at: <https://www.greenschool.org/environment/> [Accessed 18 March 2017].
- IBUKU, 2012. Turtle Classroom. [Online] Available at: <http://ibuku.com/projects/turtle-class-room/> [Accessed 10 March 2017].
- Lafargeholcim Foundation, 2013. School infrastructure from local resources. [Online] Available at: <https://www.lafargeholcim-foundation.org/Projects/school-infrastructure-from-local-resources-vele-and-vryheid-so> [Accessed 07 March 2017].
- LEED V4, 2016. Checklist: LEED v4 for Building Design and Construction. [Online] Available at: <http://www.usgbc.org/resources/leed-v4-building-design-and-construction-checklist>
- Meteoblue, n.d.a. Climate Denpasar. [Online] Available at: [https://www.meteoblue.com/en/weather/forecast/modelclimate/denpasar\\_indonesia\\_1645528](https://www.meteoblue.com/en/weather/forecast/modelclimate/denpasar_indonesia_1645528) [Accessed 10 March 2017].
- Meteoblue, n.d.b. Climate Mavhuwa. [Online] Available at: [https://www.meteoblue.com/en/weather/forecast/modelclimate/mavhuwa\\_south-africa\\_977909](https://www.meteoblue.com/en/weather/forecast/modelclimate/mavhuwa_south-africa_977909) [Accessed 10 March 2017].
- Peterson, A., 2015. Global Coalition for Green Schools Recognizes Greenest School on Earth. [Online] Available at: <http://education.usgbc.org/articles/global-coalition-green-schools-recognizes-greenest-school-earth> [Accessed 25 March 2017].
- PJCarew Consulting, 2011. Vele Secondary School. [Online] Available at: <http://www.pjc.co.za/vele-secondary-school.html> [Accessed 10 March 2017].
- Shim, B., 2010. Green School 2010 On Site Review Report , Geneva, Switzerland: The Aga Khan Award for Architecture.
- State of the Tropics, 2012. Children in the Tropics. [Online] Available at: <http://stateofthetropics.org/390-2> [Accessed 25 March 2017].
- UNESCO, 1978. UNESCO-UNEP Environmental Education Newsletter, Paris: UNESCO.
- Watt, E., 2014. 10 reasons why children don't go to school. [Online] Available at: <http://www.aworldatschool.org/news/entry/10-reasons-why-children-dont-go-to-school-1350> [Accessed 20 March 2017].
- Yong, E. A., 2010. Bali Green School Designed with Bamboo. [Online] Available at: [http://www.solaripedia.com/13/311/3483/bali\\_green\\_school\\_class.html](http://www.solaripedia.com/13/311/3483/bali_green_school_class.html) [Accessed 10 March 2017]



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The near Zero Energy Building standard and the Passivhaus standard – a case study

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**Abstract:** The EU has mandated that all buildings are built to the near Zero Energy Buildings (nZEB) standard from 2020. The Passivhaus standard has been in existence for over 25 years and potentially offers a tried and tested method of achieving nZEB. This paper explores if there is a performance gap between the PH standard and the nZEB standard. Further, analysis is carried out based on monitoring results from a real building: a 103m<sup>2</sup> three bedroom dwelling located in Ireland. The comparison of the two standards is carried out with particular focus on the assumed and recorded indoor temperature assumptions and heating periods for both standards. The analysis looks at the actual indoor climate experienced, based on the following recorded metrics which are being gathered at five-minute intervals: a) occupancy profile; b) indoor air temperature; c) indoor relative humidity; d) indoor carbon dioxide concentrations; e) outdoor temperature; f) outdoor relative humidity; g) wind speed; h) barometric pressure; i) energy consumption. Based on the above metrics a discussion takes place on the energy and IEQ performance in the context of the performance mandated by the respective standards in the quest to deliver Passive and Low Energy Architecture.

**Keywords:** Passivhaus, nZEB, Monitoring, IAQ

### Introduction

Given the planned 2020 implementation of the near Zero Energy Building (nZEB) standard in the Republic of Ireland, a comparison with the well-established Passive House (PH) standard is timely. While a number of publications have been written to investigate the potential for the Passive House standard in the Irish climate (e.g. Colclough, 2011; Clarke et al, 2012) and a number have considered net zero energy buildings, (Hernandez and Kenny, 2010, Goggins et al, 2016), none have compared the PH with the newly defined nZEB standard for the Republic of Ireland.

To comply with the Passive House standard, dwellings must consume less than 120 kWh/m<sup>2</sup>/a of primary energy, as determined by the Passive House planning package (PHPP). The nZEB standard in Ireland (to be finalised in 2019) requires that dwellings must consume less than 45 kWh/m<sup>2</sup>/a (anon, 2012), see figure 1. It therefore appears that the nZEB standard is more stringent than the Passive House standard. However, this is not a like-for-like comparison. This paper answers the question of whether a performance gap exists by comparing the derived figures for a case study of a building which has been built to the Passive House standard. In addition, initial monitoring results are presented to determine if the

dwelling is complying with the assumptions inherent in the Passive House standard and Irish building regulations.

#### Typical performance standards for nZEB for dwellings

Low Energy <sup>6</sup> Dwelling with Solar Thermal DWH	
Primary Energy (kWh/m <sup>2</sup> /yr)	45
CO <sub>2</sub> Emissions (Kg/m <sup>2</sup> /yr)	10
EPC	.302
CPC	.305

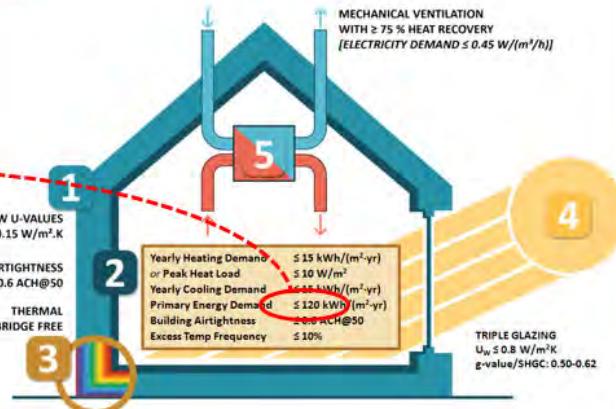


Figure 1. Comparison of nZEB and PHPP primary

#### Comparison of standards

To compare both standards correctly consideration needs to be given to the basis of the comparison, in particular with respect to the energy consumption calculations. Recognising that the calculations will vary depending on the dwelling specifics, this case study examines a house which has been designed to comply with the Passive House standard, and has been constructed by building firm Bennetts in Enniscorthy, Co Wexford, Ireland.

The house is a certified Passive House of 103 m<sup>2</sup> and is occupied by one person. It utilises an integrated HRV system which addresses the space heating and domestic hot water requirements of the dwelling, with electricity as the fuel. In addition to heating the air via a heat pump, the unit also controls two 400W electric heating elements located in the sitting room and hall.

The DEAP (Dwelling Energy Assessment Procedure) is the software used to calculate the Building Energy Rating (BER) for dwellings in Ireland and ensure compliance with the nZEB standard. The DEAP calculations were carried out on the case study dwelling, and are presented in figure 2, in addition to the calculations carried out in the Passive House Planning Package (PHPP), the software used to ensure compliance with the Passive House standard. Two figures are presented for the PHPP - "Normal PHPP", and with the PHPP modified to perform calculations on the same basis as the DEAP software ("DEAP PHPP"). Details are provided in the next section on the calculation methodology.

As can be seen, the building is compliant with the nZEB performance standards as calculated by the DEAP software, with respect to primary energy consumption, carbon dioxide emissions, Energy Performance Coefficient (EPC) and Carbon Performance Coefficient (CPC) requirements and is therefore an nZEB standard compliant dwelling.

In addition, the PHPP calculations show that the dwelling is in compliance with the Passive House standard with respect to primary energy consumption, as it consumes 91 kWh/m<sup>2</sup>/a, within the Passive House standard limit of 120 kWh/m<sup>2</sup>/a.

The case study shows that the house designed to comply with the Passive House standard, meets the nZEB requirements. However, a clear discrepancy exists between the primary energy consumption and carbon dioxide emission figures using the two methodologies. In the analysis below a comparison is made based on the specifics of the

dwelling under consideration. The analysis highlights the inherent differences in the two apparently similar primary energy consumption figures.

Table 1: Typical performance standards for NZEB for dwellings

	Low Energy <sup>6</sup> Dwelling with Solar Thermal DWH	DEAP	Normal PHPP	'DEAP' PHPP
Primary Energy (kWh/m <sup>2</sup> /yr)	45	24.37 ✓	91.1 ✗	31.2 ✓
CO <sub>2</sub> Emissions (Kg/m <sup>2</sup> /yr)	10	5.26 ✓	18.6 ✗	6.31 ✓
EPC	.302	0.159 ✓	N/R	N/R
CPC	.305	0.165 ✓	N/R	N/R

- 'DEAP' PHPP adjusted to omit plug loads, include PV production and reduce Primary Energy factor for electricity from 2.6 to 2.19
- Bennett Passive House Already NZEB

Figure 2. Comparison of nZEB calculations using DEAP, PHPP and PHPP adjusted for DEAP requirements.

#### ***Comparison of PHPP and DEAP derived specific energy consumption***

The Passive House standard calculates the primary energy required to meet all the energy needs of the dwelling (PHI, 2016) whereas the DEAP methodology bases its calculation on the building services energy load for space heating, water heating, fixed lighting and ventilation (Anon, 2012). Therefore electricity required for cooking, washing machines, clothes dryers, lighting, TV and entertainment equipment, Home Office equipment and all other plug loads are not considered. In addition, given the focus on reducing DHW and heating energy consumption in low energy dwellings to be implemented via the nZEB standard, and the significant growth in consumer electronics and electrical devices, while current building services loads in Ireland are estimated to be 50% (Anon 2015), the proportion of energy spent on building services is forecast to reduce further.

Both PHPP and the DEAP software use a primary energy conversion factor to convert the calculated energy consumed in the dwelling to the energy content of the fuel used to produce electricity in the generation stations. The PHPP calculation assumes a primary energy conversion factor of 2.6, whereas the DEAP software assumes 2.19.

When the services not included in the DEAP methodology are removed from the PHPP, and the primary enrgy conversion factor set to the DEAP version of 2.19, the PHPP primary energy demand reduces by almost 50% i.e. from 91 to 49 kWh/m<sup>2</sup>/a and when the PV contribution is subtracted, this figure drops to 31.2 kWh/m<sup>2</sup>/a.

Table 1 shows other differences in the DEAP and PHPP methodologies used. Of particular note is the floor area calculation. The PHPP works on the basis of the Treated Floor Area, TFA (PHI, 2014), which excludes areas included in the assumed DEAP calculation methodology such as the floor area associated with stairs, internal walls etc. The difference between the TFA and the DEAP floor area varies based on the geometry of the individual dwelling. In the case of the house under consideration the PHPP underestimates the house size by 10%, therefore over estimating the specific energy consumption.

Table 1. Basis of calculation methodologies for DEAP and PHPP.

	<b>DEAP Model</b>	<b>PHPP Model</b>
<b>Basis for model</b>	Benchmark house	Bespoke model for each design
<b>Validation of performance</b>	Unpublished	Scientifically validated
<b>Floor area calculation</b>	Gross	Net ("Treated Floor Area") (excludes internal walls and stairs)
<b>Heating duration</b>	8 hours per day	24 hours per day
<b>Winter Interior Temperature</b>	~ 18.5°C Average based on typical Irish dwelling layouts for 8 hrs per day	20°C throughout
<b>Summer Interior Temperature</b>	Overheating not predicted	25°C Max for 10% of year
<b>Radiant Temperature Asymmetry</b>	Not considered	Avoided
<b>Unintended air infiltration</b>	< 7 m³/m²/hr @ 50Pa	< 0.6 ach⁻¹ @ 50Pa
<b>Ventilation rate</b>	Not required	15m³ fresh air per person per hour

If the average temperature is reduced from the PHPP normal temperature of 20°C to the DEAP equivalent temperature for the reference dwelling of 18.5°C, the PHPP figure drops to 24 kWh/m<sup>2</sup>/a and when the floor area is adjusted to the DEAP assumed figure, the PHPP derived specific primary energy consumption figure drops to 19 kWh/m<sup>2</sup>/a.

Therefore without taking into consideration that the heating period in a Passive House is 24 hour compared with the DEAP assumption of 8 hours per day, the PHPP adjusted consumption figure is 19 kWh/m<sup>2</sup>/a where the DEAP software assumes 24.4 kWh/m<sup>2</sup>/a.

## Recorded Performance

The house has been monitored since August 2016.

### ***Temperature and carbon dioxide***

Figure 3 gives the temperature charts for the three month period October, November, December 2016 for the kitchen, living room and bedroom. In addition to providing an insight into the thermal comfort of the dwelling, the analysis allows a comparison of monitored internal temperatures, against those predicted by the Passive House Planning Package software and the DEAP software.

It is noted that the monitoring units deployed in the dwellings are commercially available units which are not of laboratory grade. While the units have been found to be calibrated correctly with respect to temperature, some units have been found to be outside the specified limits for relative humidity and carbon dioxide concentration. Thus, readings outside the threshold levels indicate that further investigation may be warranted.

Passive Houses are designed to have a uniform temperature of 20°C throughout. A temperature threshold has therefore been set at 20°C to aid analysis of the performance against the Passive House standard.

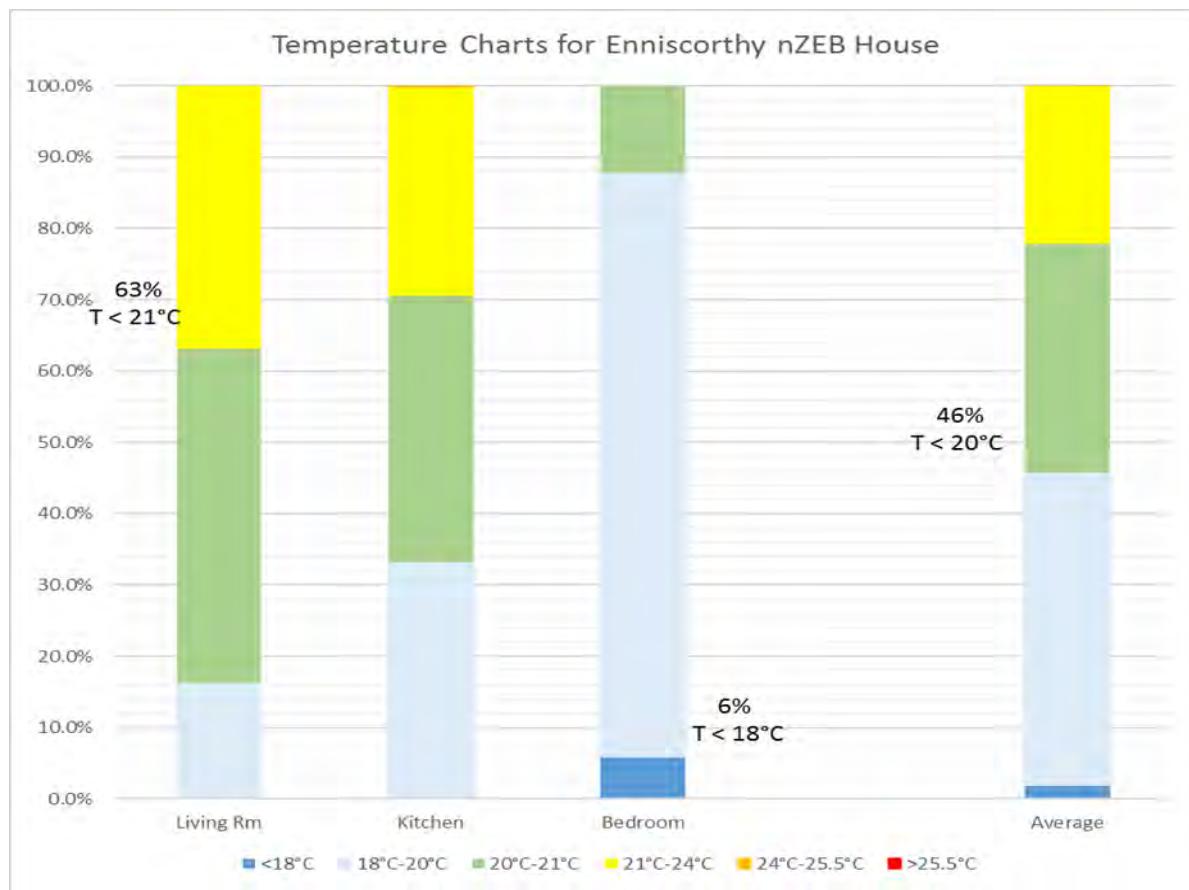


Figure 3. Temperature Chart for Enniscorthy nZEB House, October, November and December 2016.

The Republic of Ireland's Dwelling Energy Assessment Procedure (DEAP) assumes a two-hour heating period in the morning (7 AM to 9 PM), as well as six-hour heating period in the evening (5 PM to 11 PM), during which time the heating system is assumed to have a set temperature. The DEAP software assumes a set temperature of 21°C for the living room and 18°C for the "rest of dwelling" i.e. outside the living area. Thus 18°C and 21°C have been chosen as threshold temperatures in the temperature charts in Figure 3.

The temperature in the living room, kitchen and bedroom exceeds the Passive House set temperature of 20°C for 84%, 67% and 12.3% of the time respectively, leading to an overall figure of 54% of the time when the temperature is above the set temperature of 20°C. The relatively low temperatures in the bedroom are due to a personal preference by the occupant.

The temperature in the living room, kitchen and bedroom exceeds the building regulations set temperatures 37%, 100% and 94% of the time respectively. It is noted that further analysis could be carried out to determine the periods of time for which the temperatures exceed the set temperatures during the DEAP specified heating periods.

Figure 4 gives the carbon dioxide concentrations for the dwelling. Overall, the CO<sub>2</sub> concentrations are seen to be below 1000 ppm for 97% of the time, reflecting the relatively low occupancy profile.

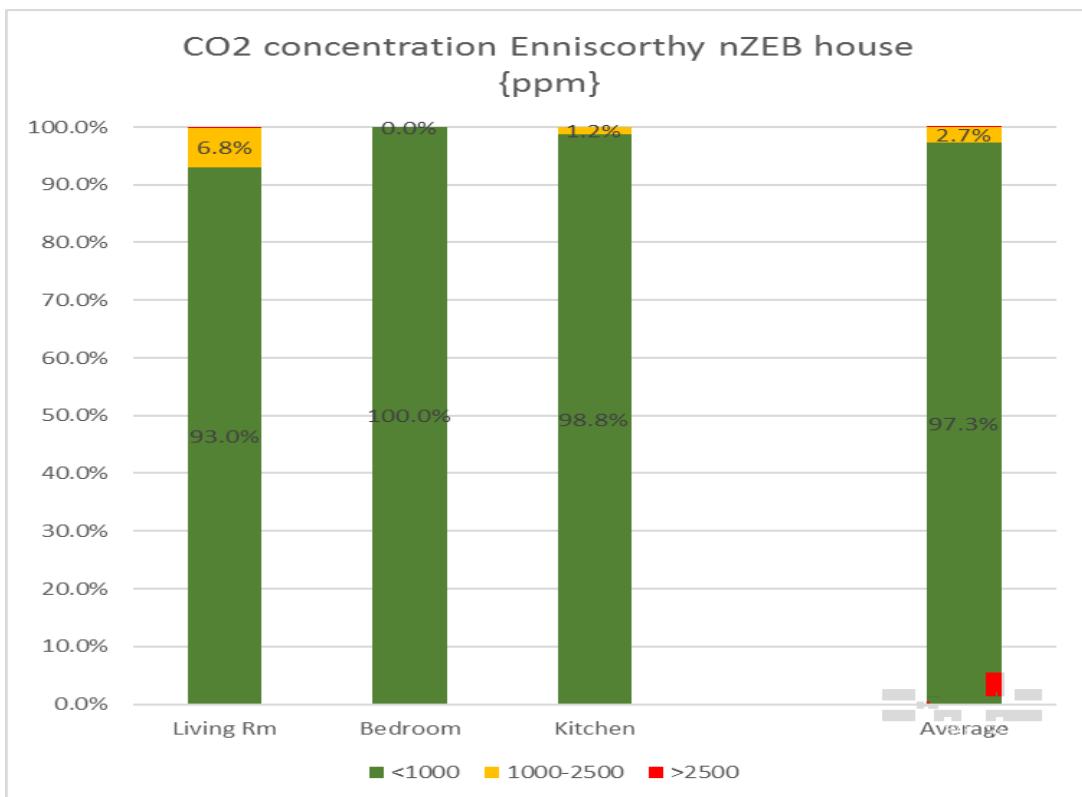


Figure 4. Carbon Dioxide Concentration Chart for Enniscorthy nZEB House.

### **Energy consumption**

Figure 5 shows the heating and ventilation energy consumption of the dwelling for six months of September 2016 to March 2017 along with the overall energy consumption. The annual consumption is therefore not available, but will be reported on in a future publication.

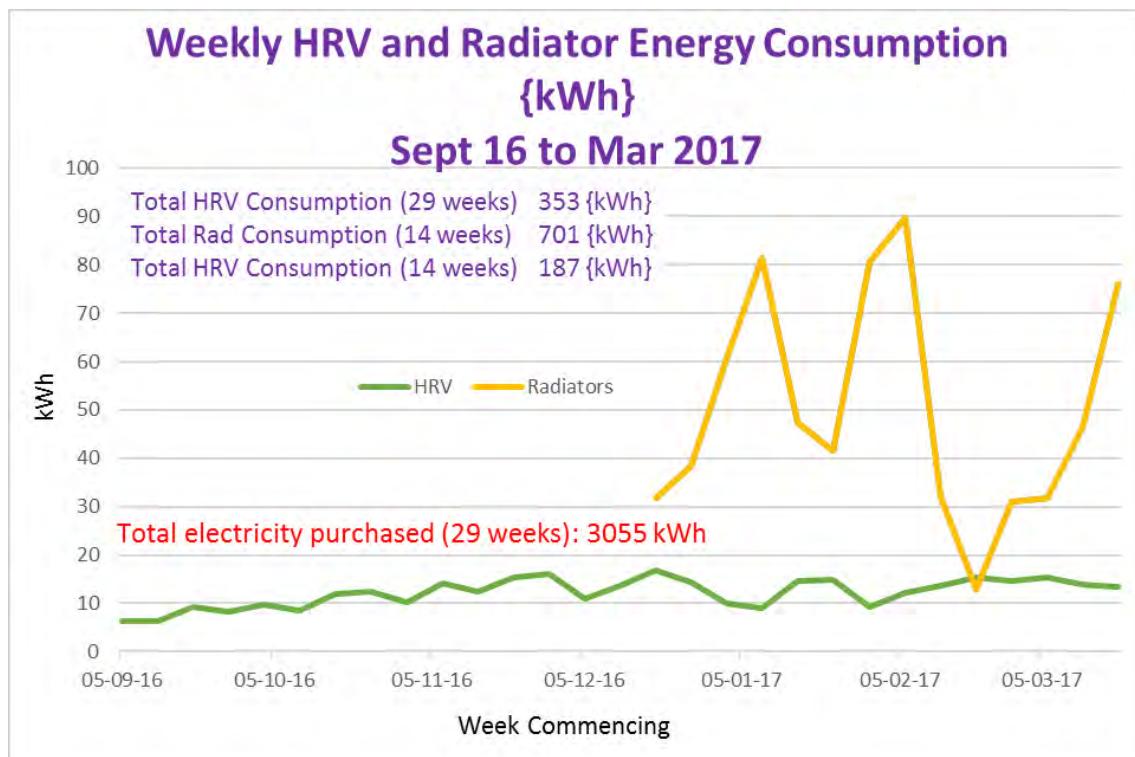


Figure 5. Energy Consumption for Enniscorthy nZEB House.

DHW and space heating energy consumption for the 14 week (w/c 19/12/2016) period was recorded at 888 kWh equivalent to 8.6kWh/m<sup>2</sup>/a (based on 103 m<sup>2</sup>), or 9.5 kWh/m<sup>2</sup>/a based on a treated floor area of 93 m<sup>2</sup>. The Passive House standard requires less than 15 kWh/m<sup>2</sup>/a for space heating alone, so even allowing for 6.6% lower than average heating degree days for the period, it appears that the certified Passive House is performing within expected parameters. The dwelling also appears to be performing within the DEAP maximum energy consumption of 45 kWh/m<sup>2</sup>/a, as 888 kWh is equivalent to 18.9 kWh/m<sup>2</sup>/a (based on 103 m<sup>2</sup> and a primary energy conversion factor of 2.19). It is noted that while this figure does not include lighting, it does include DHW, space heating and ventilation energy consumption, and covers the period which typically reflects the greatest heating demand.

Overall electricity energy purchase from the grid for the 29 week period is 353 kWh, equivalent to 65 kWh/m<sup>2</sup>/a (based on 103 m<sup>2</sup>) of primary energy (at a conversion factor of 2.19).

## Conclusion

This analysis has shown that a certified passive house designed using the Passive House Planning Package is compliant with the nZEB requirements. Using the DEAP building energy rating software, the dwelling is deemed to consume 24 kWh/m<sup>2</sup>/a, significantly below the 45 kWh/m<sup>2</sup>/a required for nZEB compliance.

The monitoring found that the house is performing within expected limits. The temperature in the living room, kitchen and bedroom exceeds the Passive House set temperature of 20°C for 84%, 67% and 12.3% of the time respectively, and exceeds the building regulations set temperatures 37%, 100% and 94% of the time respectively. The indoor air quality is also good with carbon dioxide concentrations in the living room, kitchen and bedroom staying below 1000 ppm for 93% 98% and 100% of the time respectively.

Overall DHW and space heating energy consumption for the 14 week period (w/c 19/12/2016) was recorded at 888 kWh, equivalent to 8.6kWh/m<sup>2</sup>/a, of which 187 kWh was for operation of the heat recovery ventilation unit. Monitoring is continuing to determine the annual energy performance and IEQ of the dwelling.

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## References

- ANON, 2015. *Energy Efficiency Trends and Policies in the Household and Tertiary Sectors*. EU Intelligent Energy Europe.
- ANON, 2012. *Towards Nearly Zero Energy Buildings in Ireland, Planning for 2020 and Beyond*. Dublin: Department of Environment, Community and Local Government.
- CLARKE, J., COLCLOUGH, S., GRIFFITHS, P. and MCLESKEY, J.T., 2014. A passive house with seasonal solar energy store: in situ data and numerical modelling. *International Journal of Ambient Energy*, (1), pp. 35-70.
- COLCLOUGH, S.M., 2011. *Thermal energy storage applied to the Passivhaus standard in the Irish climate*, University of Ulster.
- COLCLOUGH, S. and MCGRATH, T., 2015. Net energy analysis of a solar combi system with Seasonal Thermal Energy Store. *Applied Energy*, **147**, pp. 611-616.
- GOGGINS, J., MORAN, P., ARMSTRONG, A. and HAJDUKIEWICZ, M., 2016. Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland. *Energy and Buildings*, **116**, pp. 622-637.

HERNANDEZ, P. and KENNY, P., 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings*, **42**(6), pp. 815-821.

PHI, 2016-last update, Passive House Planning Package. Available: [https://passipedia.org/planning/calculating\\_energy\\_efficiency/phpp\\_the\\_passive\\_house\\_planning\\_package](https://passipedia.org/planning/calculating_energy_efficiency/phpp_the_passive_house_planning_package).

PHI, 2014-last update, Energy balances. Available: [https://passipedia.org/planning/calculating\\_energy\\_efficiency/energy\\_balances - background](https://passipedia.org/planning/calculating_energy_efficiency/energy_balances - background).

SEAI, 2012. *DEAP Manual, Version 3.2.1*.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Limitations of Environmental Assessment Methods for Bioclimatic Building Design

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**Abstract:** The Leadership in Energy and Environmental Design (LEED) assessment standard has been successful in bringing sustainability to the mainstream of building design, and communicating a measure of environmental quality. There is a tendency in the literature as there is in the construction market to use a LEED score as a proxy for high performance construction. This proclivity obscures the processes and priorities that informed the building design, as well as differences in the performance and context of similarly rated buildings. In contrast to the LEED framework, bioclimatic design proposes to minimize environmental impact and energy demand through the implementation of passive design strategies which *cater to* site-specific conditions. Little work has been done on the ability of LEED to measure bioclimatic integration in the design approach. The aim of this paper is to understand (a) the interaction between the LEED framework and the bioclimatic design approach, and (b) how project-level and contextual dynamics influence the energy performance of buildings. This paper challenges the use of LEED as a tool to support a transition to a sustainable building industry, and suggests that environmental assessment should focus on both performance-based energy use intensity targets, and the integrative approach of the design process itself.

**Keywords:** Bioclimatic, environmental assessment, LEED, passive-design

### Introduction

Energy consumption and the resulting Greenhouse Gas (GHG) emissions from buildings comprise up to 40% of the total quantities emitted by developed countries (IPCC, 2014). The Intergovernmental Panel on Climate Change IPCC (2014) suggest that if sustainability is successfully incorporated into the building sector, it is possible to reduce GHG emissions by 6 Gt per year worldwide. Furthermore, the International Energy Agency (IEA) has identified the building sector as one of the most cost-effective industries for reducing CO<sub>2</sub> emissions associated with energy demand (Giama and Papadopoulos, 2012). Due to this potential, laws, policies and regulations requiring integration of sustainability into the built form are becoming increasingly common on a global scale (Berardi, 2012). In many cases, regional policies are incorporating environmental assessment methods (EAMs) as a strategy to encourage emissions reductions associated with the construction sector (Berardi, 2012; Hellstrom, 2007; Steurer and Hametner, 2011).

EAMs are rating systems that have been developed as a tool for the valuation of the environmental impacts of 'green' or high performance buildings. The LEED rating system was developed by the US Green Building Council (USGBC) in 1998, as a market tool 'to provide building owners and operators a concise framework for identifying and implementing

practical and measurable green building design, construction, operation and maintenance solutions,' (Azhar et al, 2011, p. 217).

Canadian Green Buildings Council (CaGBC) has administered LEED-British Columbia; a version of the assessment method which is licensed to Canada by the USGBC and apparently designed to meet the specific needs of the Vancouver market. LEED-Canada for New Construction version 1.0 is based on assessment in six categories, including (a) Sustainable Sites (14 points), (b) Water Efficiency (5 points), (c) Energy and Atmosphere (17 points), (d) Material and Resources (14 points), (e) Indoor Environmental Quality (15 points), and (f) Innovation and Design Process (5 points). Buildings can achieve performance ranging from certification (26 points), silver (33 points), gold (39 points), to platinum (52 points).

With aims to be the world's greenest city, the City of Vancouver is proposing that all new construction be carbon neutral by 2020. The City of Vancouver has identified LEED as an important part of incentivizing the transition. Although it was initially designed to be voluntary, the CaGBC LEED Strategic Direction Plan 2014-2016 explicitly describes their goal of achieving marketplace transformation through advocating and supporting the integration of LEED into building policy. City re-zoning bylaws require all new construction to meet the LEED Gold certification level (City of Vancouver, 2014).

An extensive body of research has explored the limitations of the LEED framework for assessing high performance building design. The most widespread criticisms include its inability to adapt to regional priorities, contexts, and users; all factors which have been found to significantly influence a building's energy performance (Li et al., 2015). Further, certification levels are based on the designed energy use rather than actual energy use, and thus LEED does not address the performance gap which is common to both certified and uncertified buildings (Li et al., 2015). Although LEED scores tend to be perceived as proxy for high performance construction by the public and property market, LEED certified buildings are not providing the energy savings that their certification levels indicate (Li et al., 2015). These initial findings raise serious questions about the ethics and effectiveness of using EAMs as a policy tool.

In contrast to the LEED framework, bioclimatic design proposes to minimize environmental impact and energy demand by *catering* to site-specific conditions (Tzikopoulos, 2005). Existing literature describes bioclimatic architecture as designs that consider and integrate: topography, movement of the sun, climatic conditions, environmental conditions (daylighting and shading), building massing, building code, and materiality. Structures are designed to maximize solar gains, minimize heat losses during the winter months, and limit solar exposure in order to adapt various cooling techniques during the summer (Tzikopoulos et al, 2005). Intrinsic to the design concepts are passive strategies for reducing energy demand. Understanding how bioclimatic principles can be successfully integrated into the design process is a crucial factor for reducing the GHG emissions associated with the building sector. On average, bioclimatic buildings consume 50% less energy than conventional buildings, and best-practice examples have been recorded to achieve 75% savings (Tzikopoulos, 2005).

The juxtaposition of the prolific use of LEED within the policy environment in Vancouver, against the extensive volume of research documenting the limitations of environmental assessment methods, against the effectiveness of the bioclimatic design approach, has informed the research questions on which this paper is based: (1) Are LEED-rated buildings successful in meeting a bioclimatic definition of sustainable design? (2) How do project-level differences and dynamics contribute to and limit environmental performance? (3) Are

environmental assessment methods the appropriate tool for supporting the transition to sustainable built environments? The findings of this paper are based on a multi-case study of the University of British Columbia Centre for Interactive Research on Sustainability (CIRS) LEED-rated Platinum, and the Marguerite Ford Apartments (MFA) LEED-rated Gold.

## Methods

Because there is no typical ‘bioclimatic geometry,’ or combination of technologies that would suggest a design is ‘bioclimatic,’ it is necessary for the purpose of this study to define indicators that would likely suggest successful integration of bioclimatic design. The most reliable indicator of high performance construction described in the literature is the actual energy use of the building (Li et al., 2015). As such, the post-occupancy Energy Use Index (EUI) of each case will be utilized as one of the indicators of successful bioclimatic integration. The most commonly installed energy-efficient technologies (daylighting, high-efficiency HVAC, and improved envelopes) are not statistically associated with low EUI (Li et al., 2015). Instead, it is the way that these technologies are integrated, and the relationships between technologies, occupants, and building context that is indicative of EUI. The analysis of the results will thus focus on the integrative approach of each design team, and their understanding of how these systems, technologies and passive strategies operate together, rather than focusing on the presence of energy efficient technologies.

In order to explore the research questions, this paper will examine the EUI, design approach and LEED score for each case.

### **Results: Are LEED-rated buildings successful in meeting a bioclimatic definition of sustainable design?**

#### **CIRS**

The CIRS building is a sustainability-focused research centre located on the University of British Columbia (UBC) Vancouver campus. The principal use of the building is for research, education and administration. CIRS is occupied by researchers, students, staff, and public visitors. The CIRS building is owned and operated by UBC, who have a history of pursuing operational sustainability goals and targets in its developments. On the UBC campus, all building projects must be certified to LEED Gold as of 2009. Data for this case is largely based on the Technical Manual published to UBC’s website.

#### *Energy Use and LEED Score*

In the LEED scoring system, the percent improvement over a baseline model determines the project score in the Optimize Energy Performance (OEP) sub-category within the Energy and Atmosphere category. The baseline energy use for this building type is 219.1 kWh/sq.m/yr, and the design team modelled improvements over the baseline target of 100%. The design achieved 10/10 points in the OEP sub-category (Table 1). According to the CIRS website, the current post-occupancy EUI is approximately 130 kWh/sq.m/yr, which is a 32% reduction over the baseline EUI (Table 1).

Table 1. The LEED score in the ‘Energy and Atmosphere’ category, and EUI for each case.

	CIRS	MFA
LEED Scorecard: Energy and Atmosphere (17 Possible Points)	15	12
Baseline Energy Performance (kWh/sq.m/yr)	219.1	250
Design EUI	0	95
Post-Occupancy EUI	130	123
Actual Energy Reduction Over Baseline Model (%)	32%	51%

CIRS’ score in Energy and Atmosphere is the highest of both cases, but is not reflective of its post-occupancy building performance. Rather, the score is reflective of the proposed system design, and of the incorporation of renewables. CIRS has extensive incorporation of photovoltaics, which are not providing as much energy as planned. The use and positioning of the collectors for optimized energy production is not specified in the Technical Manual.

A 3000 point monitoring system provides feedback on energy consumption; natural ventilation rates; daylighting performance; artificial illumination levels; airflow and exchange rates; and surface and air temperature. CIRS has received a credit for Measurement and Verification, and UBC plans to continue to measure building performance intensively. Although the building is not performing as intended, it is important for the owner to demonstrate that the implemented systems are able to perform. There is thus a long-term commitment to having CIRS reach its original net-zero goal; a commitment that is not acknowledged by LEED and is likely not commonplace for projects who have pursued the Measurement and Verification credit.

The case study also reports that graduate students at UBC performed a post-occupancy study which found positive feedback from the occupants, specifically concerning some of the social benefits that CIRS provides: ‘They particularly like the sense of community of the building, as well as the opportunities it creates for social interaction (facilitated by open spaces designed for that purpose)’ (CIRS Technical Manual). Such social benefits are not acknowledged by the LEED framework.

#### *Design Philosophy*

The design processes and philosophy of both the architectural firm and UBC have an obvious bioclimatic focus. The team considered how the building would perform in different seasons, explored different massing options, focused on occupant comfort, and tailored the design to site-specific conditions including climate, microclimate, users, and occupants. Architecturally, this is expressed via different responses on each building façade. Utilizing the waste heat from the neighbouring building also demonstrates the team’s focus on contextual considerations.

#### **MFA**

The MFA building is a multi-unit medium-rise social housing apartment complex. 80% of the occupants are at medium to high risk of homelessness and 20% of occupants are those who qualify for low income housing. The building is owned by BC Housing, operated by Katherine Sanford Housing Society. Data for this case is based on the survey responses and interviews with key informants.

#### *Energy Use and LEED Score*

The design EUI for MFA was 95 kWh/sq.m/yr, which is a 62% improvement over the proposed baseline energy performance of 250 kWh/sq.m/yr. They received 8/10 points for their OEP

Score. The actual EUI of the building during its first year of occupation was 123 kWh/sq.m/yr, which is a reduction of approximately 51% relative to the proposed baseline EUI.

In Energy and Atmosphere LEED category, the MFA building has achieved a lower score than CIRS. The low score is indicative of the level of renewables that were incorporated into energy system design, but does not reflect the post-occupancy energy performance. The client's commitment to energy performance is not acknowledged by LEED, as only one point is allocated for post-occupancy monitoring.

According to the survey respondents, design features that were included in the design, but not acknowledged by LEED include some of the durability features of the building, social spaces, vegetable gardens, and landscaped areas which were designed based on the micro-climate of the site. The numerous important social benefits and services provided by MFA are also not acknowledged by LEED.

### *Design Philosophy*

The requirement of BC Housing for reduced operational costs and a durable building has resulted in a strong commitment by the client, design team and building operators to improving the environmental performance of the building over the course of its lifetime. The importance of solar access and a high-performance envelope is also an important part of the architect's environmental philosophy. This commitment inherently required a level of bioclimatic integration on behalf of the design team. The design team has also utilized a user-based design approach that is built around addressing the social and health concerns of its occupants as well as optimizing livability and comfort. The building design maximized the lot size in order to achieve as many units as possible within the parameters set by the community plans. As a result, the orientation of the building was predetermined with the design focus on the performance of the building envelope in order to limit heat losses and undesirable solar gains. There was a strong understanding and consideration of the trade-off of passive strategies, and those that were selected were the best fit for the user and the client. Budgetary restraints were significant for this project, especially compared to the other case, and the importance of responding to the specific and pressing needs of the occupants of this building presented a barrier to bioclimatic integration. The landscape architect also noted that it is commonplace to prioritize views and aesthetics over context-based design and that this project was not an exception. He suggested that each façade should respond to its specific micro-climate, but this was not the case for MFA.

### **Results: How do project-level differences and dynamics contribute to and limit environmental performance?**

The following section will focus on identifying some of the project-specific factors that have been influential in determining building performance and the level of bioclimatic integration and comparing the contextual differences of each case.

### ***Modelling***

An emergent theme in the analysis of the design team-consultant-contractor relationships was the use of building information modelling. The use of BIM allows for multi-disciplinary contribution to a single building model, increased accuracy for the analysis of building performance, and can be an important tool for the integration of bioclimatic design (Motawa and Carter, 2013). The CIRS team reported the importance of BIM for engaging the general contractor early in the design process. The model helped the team to identify structural issues with the design earlier, increased coordination among consultants and between designers

and contractors, and helped the team to produce a more accurate bid (University of British Columbia, 2011). BIM was not used in the MFA design process. As Santos-Brault, environmental consultant for MFA described, the use of BIM is more challenging when every consultant is from a different company as was the case for this project. BIM also adds a significant project cost, and is only useful if building operators have enough experience to optimize the use of the model. In the case of MFA, non-profit operators required a simplified interface in order to be involved in the design process.

### ***Design Priorities***

According to the design team, BC Housing's priorities included maximizing the use of the lot, meeting the needs of the client, building durability, energy performance, and reducing operational costs. This prioritization is reflected in the post-occupancy energy performance of the building, and the numerous design features integrated for the purpose of meeting the needs of the occupant. The client was looking for more durable construction opposed to high-end architectural finishes. It is not typically what most contractors would see, as the architectural finishes are normally one of the biggest expenses. A more practical architectural design left more of the budget to allocate towards the high-performance envelope. The expression of idealized concepts in this case were limited by client's need to respond to the user and also by budgetary constraints.

As an academic institution aiming to practice what they are teaching their students, the architectural expression of CIRS is equally important as demonstrating the effectiveness and replicability of its systems. If the achievement of net-zero targets had been the only priority, this project likely had the resources, knowledge, and experience to achieve that; however, it was also important for UBC to put these systems on display, to test multiple systems, and to integrate the latest technologies throughout the lifetime of the building. Hence, the client's commitment to achieving net-zero is not reflected by the EUI.

### ***Building Operations and End-Users***

The requirements of the occupants at MFA necessitated the commissioning of a non-profit housing society to operate the building. Katherine Sanford Housing Society has experience working with tenants who are effected by mental disorders and social issues. Their feedback was required throughout design development and remains to be valuable following the completion of construction (Santos-Brault, Personal Communication, 2015). On the other hand, the individuals maintaining the building systems do not have time to effectively engage with these massively complicated systems (Bigourdin, Personal Communication, 2015). Although the society does not have experience operating a high performance building, many efforts were put in place by BC Housing to advance learning and ensure that the building can perform how it was designed to. Occupants at MFA are not aware of their energy consumption (Forsyth, Personal Communication, 2015), and have no previous experience or education regarding high performance construction. BC Housing noted that putting efforts into education for occupants has not been as effective as they had hoped. CIRS, on the other hand, has experienced building operators who have been trained in the maintenance and operations of high performance construction. Further, the users and operators of CIRS are industry experts in the fields of sustainable construction.

Understanding the nature of the dynamics that allow energy performance to become a high priority for the client and design team helps to identify some of the barriers and incentives for this prioritization. In terms of the collaborative approach of each project, some

of the incentives for designing a building with low energy demand described in this section include (a) client prioritization of low energy demand or operating costs, (b) exploring the performance of several iterations of the design through the use of BIM and other software, and (c) having an experienced building operator and educated occupants. Barriers to achieving high performance design include the high prioritization for many clients of the appearance of sustainability over post-occupancy energy performance, and the prioritization of user needs over energy performance. This analysis only scratches the surface to describe emergent themes between cases, and future studies should cover a more in depth analysis of the project dynamics of each case.

### **Conclusion: Are environmental assessment methods the appropriate tool for supporting the transition to sustainable built environments?**

The bioclimatic design approach necessitates the consideration of the building's climatic, social, economic, and cultural context. It requires a deep understanding of the ways that passive solutions are integrated in design, trade-offs between the implementation of particular strategies, and consideration of how design strategies will interact with the user after construction is completed. Although LEED acknowledges the use of passive strategies, it is unable to allocate points for how design components, systems, and strategies are interacting or how they are being integrated. The Energy and Atmosphere category is not performance based, and its requirements promote technology-based strategies for energy reduction. Instead of promoting substantial reduction in energy demand, LEED promotes relatively small improvements in energy efficiency. A design approach that perceives LEED requirements as boxes that need to be ticked only to improve the market value of the end result could potentially achieve a high level of certification by integrating efficient technologies. Conversely, user-specific, low-tech, low-energy building design may not meet sufficient LEED requirements to be certified, making it difficult for this type of approach to gain recognition in the current market.

The project level-dynamics explored in this study both contribute and limit the environmental performance of each case. The nature of the collaborative approach of a project, the design approach and priorities, and the influence of the building operator and user are some of the identified dynamics that are important for determining post-occupancy building performance. These findings exemplify that architecture is not only the work of architects, but the co-production of engineers, contractors, consultants, politicians, owners, users, and the building itself. In the cases under study, the architects are acting as mediators to manage compromises and various interests to come to a solution that aligns with the needs of all actors in the assemblage, including their own.

LEED has a dominant position in the industry and has been successful in engaging with many sectors of the building industry at multiple scales. It has become a policy tool, played a role in increasing industry and public awareness of sustainable buildings, and an increasing number of industry professionals and owners are registering their projects for certification. Whether LEED remains to be an effective tool to support a transition to a sustainable building sector is challenged in this study. Despite the dominance and influence of the LEED, the framework has a limited ability to assess environmental performance. The newest version of LEED, V4, incorporates some performance-based metrics for the assessment of indoor environmental quality and occupant comfort; however, performance based EAMs would continue to place value on an end *product*, rather than the design *process*. Understanding how to integrate an assessment of the design process itself within LEED could be an important

leverage point for triggering the necessary shift in the building sector. In order for the building sector to engage with new ways of designing, the benefits of the bioclimatic approach need to be exemplified to the industry. Policy and government incentives should play a role in supporting this demonstration by making genuine low-energy construction more affordable for both small and large companies. It is important to engage with the industry to find out what areas require innovation, research, funding, and skills, in order for small- or medium-sized developers to produce low emissions construction and engage with bioclimatic concepts.

## References

- Azhar, S., Carlton, W.A., Olen, D., and Ahmad, I. (2011). Building Information Modeling for Sustainable Design and LEED Rating Analysis. *Automation in Construction*, 20, pp. 217-224
- Berardi, U. (2012). Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings. *Sustainable Development*, 20(6), pp. 411-424
- City of Vancouver. (2014). *Green Buildings Policy for Rezonings*. Vancouver: City of Vancouver
- City of Vancouver. (2014). *Greenest City 2020 Action Plan: Implementation Update*. Vancouver: City of Vancouver
- Giama, E., and Papadopoulos, A.M. (2012). Sustainable Building Management: Overview of Certification Schemes and Standards. *Advances in Building Energy Research*, 6(2), pp. 242–258.
- Hellstrom T. (2007). Dimensions of Environmentally Sustainable Innovation: The Structure of Eco-Innovation Concepts. *Sustainable Development*, 15(3), pp. 148–159
- IEA. (2010a). *Energy Technology Perspectives 2010: Strategies and Scenarios to 2050*. Paris: International Energy Agency
- IPCC. (2014). *Summary for Policymakers: Climate Change Synthesis Report*. New York: Cambridge University Press
- Li, C., Tianzhen, H., and Yan, D. (2015). An Insight into Actual Energy Use and its Drivers in High-Performance Buildings. *Journal of Applied Energy*, 131, pp. 394-410
- Motawa, I., and Carter, K. (2013). Sustainable BIM-based Evaluation of Building. *Social and Behavioural Sciences*, 74, pp. 419-428
- Recollective. (2015). *14 Supportive Housing Sites LEED Summary Report*. Vancouver: BC Housing
- University of British Columbia. (2011). *Building Information Modeling Best Practice Project Report*. Vancouver: University of British Columbia
- Steurer R, and Hametner M. (2011). Objectives and Indicators in Sustainable Development Strategies: Similarities and Variances Across Europe. *Sustainable Development*, 20(1), pp. 321-337
- Tzikopoulos, A.F., Karatza, M.C., and Paravantis, J.A. (2005). Modeling Energy Efficiency of Bioclimatic Buildings. *Energy and Buildings*, 37, pp. 529-544
- University of British Columbia (2015). *CIRS Technical Manual*. ([http://cirs.ubc.ca/sites/cirs.ubc.ca/files/1\\_ExecutiveSummary.pdf](http://cirs.ubc.ca/sites/cirs.ubc.ca/files/1_ExecutiveSummary.pdf), August 31, 2015)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## [Re] Measuring [LEED] Sustainability: From a Global Rating System to Tropical Specificity

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**Abstract:** This paper explores the applicability of the LEED certification system through the case study of Puerto Rico (P.R.), a United States (U.S.) Commonwealth island in the Caribbean, where LEED has become widely recognized as a standard because of the geopolitical relationship with the mainland. Although LEED is used internationally, it was initially developed by the U.S. Green Building Council as a tool to measure building performance in a modern American urban environment with temperate climate, a steady economy and easy access to technology. Furthermore, regionalization strategies such as Regional Priority Credits (RPCs) and Alternate Compliance Paths (ACPs), do not address the sociocultural reality of many regions. Therefore, the focus of this research is to analyse what indicators should be added, modified or substituted to develop a revised LEED model for the specific sociocultural context of P.R.? A mixed methods research will be used to compare LEED criteria with Sustainable Assessment Systems (SAS) such as the Building Research Establishment Environmental Assessment Method, the Living Building Challenge and SB Tool. Also, SAS in tropical countries such as Singapore (BCA Green Mark), Costa Rica (RESET) and India (TERI-GRIHA) will be examined. Case studies will be analysed with a main focus in Schools.

**Keywords:** Sustainable building, School design, Socio-cultural indicators, Green building rating systems, LEED

### Green Building, Certification Systems and Regional Adaptation

#### *Introduction to green buildings and sustainability dimensions*

Several definitions of sustainability and green building since the 1970s, emphasize on energy, water and materials efficiency; the reduction of environmental impact during the construction phase; as well as the health and wellbeing of building occupants (USGBC Media, 2016; Office of the Federal Environmental Executive, n.d.:8; EPA, 2016). However, “Our Common Future”, also known as the Brundtland Report (1987), stressed the need to target **social** and **economic** aspects in addition to the **environmental** considerations required to achieve sustainable development. While environmental sustainability is concerned with the protection of nature and its resources, its social counterpart deals with the protection of basic universal human rights, such as education; equity; health; safety and security, among others (Axelsson et al., 2013:218; Energy and Resources Institute et al., 2014:59; Walker, 2014:14).

Recent models, such as the “sustainability square”, include **culture** as the fourth pillar, alongside the social, economic and ecological dimensions (Ebert 2011:21, Mateus and

Bragança 2011:1962). While the term encompasses the characteristics of a society, its norms, values, skills, knowledge and beliefs, this new approach aspires to strengthen the cultural sector; and promote its integration in policies related to education, economy and communication, among others (Axelsson et al. 2013; United Cities and Local Governments, 2010:4). The socio-cultural dimensions of sustainability will be further explored throughout this investigation, to demonstrate its application to current certification systems.

### ***Certification systems in Puerto Rico as case study***

Worldwide, certification or ‘sustainable assessment’ systems (SAS) such as the Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), among others have provided a framework of reference by including criteria and objectives of what a sustainable building should be.

These systems have been used worldwide to rate buildings beyond their country of origin. This is also the case of Puerto Rico, an island located in the Caribbean, which holds the largest amount of certified projects in the region (USGBC, 2016). Being a United States Commonwealth, the LEED SAS has become the most widely recognized standard because of the geopolitical relationship with the mainland. While P.R. shares a common Hispanic background with nearby countries, green building is subject to U.S. laws, building codes and regulations even though its culture, climate, construction systems and native language are different.

### ***School Sustainable Assessment Systems (SAS)***

Sustainable Assessment Systems such as LEED and BREEAM, among others, are mostly based on weighting building performance and environmental impact mitigation through resource consumption, mechanical systems efficiency and overall site planning. However, these criteria might overlook critical social components when assessing educational institutions. Schools, which influence the students’ views toward society and the environment and in addition to being the learning centre for more than 75% of the K-12<sup>1</sup> student population in Puerto Rico (Instituto de Estadísticas de P.R., 2014:13), makes the focus of this investigation to assess the applicability of LEED for Schools under the *Schools for the 21st Century* program. This federally funded<sup>2</sup> program included the “modernization, renovation, or repair of public school facilities”, which had to be certified, verified or consistent with LEED or other equivalent program (U.S. Department of Education, 2009; U.S. Senate, 2008:22099). This project was extended to all 78 municipalities and promoted Puerto Rico’s largest public school improvement program in decades (Fielding Nair, n.d.: 3)

The present study analyses and questions the validity of U.S. LEED as a reliable tool to evaluate buildings in the tropical Caribbean region with distinctly different environmental, economic, and socio-cultural conditions, to revise current and propose new sustainability indicators that could contextualize this system in P.R., for the particular case of Schools. Also, to assess USGBC’s regionalization strategies such as Regional Priority Credits (RPCs), used as part of the LEED for Schools certification process in P.R. to attempt to adapt the system to the local context. Other strategies for climatic adaptation, Alternate Compliance Paths (ACPs) and Innovation in Design credits, will be analysed to determine their applicability.

<sup>1</sup> Based on the U.S. and P.R. Educational system, which names school levels prior to college as kindergarten (K) through the 12th grade (12).

<sup>2</sup> The American Recovery and Reinvestment Act (ARRA) signed in 2009 by U.S. President Barack Obama, was developed to stimulate the economy of the U.S. and its Territories, including P.R. (“ARRA- Puerto Rico,” 2012).

This paper will discuss and demonstrate the gaps in current LEED indicators in regard to socio cultural factors as part of a larger body of work going on a PhD research project focused on the following objectives:

1. To inform how and determine if the U.S. LEED certification program addresses social and cultural elements as sustainability indicators.
2. To analyse why and propose how LEED indicators and regionalization initiatives by the USGBC could be modified to respond effectively to the tropical context of P.R.
3. To identify what aspects of sustainability<sup>3</sup> in the tropical Caribbean P.R. region are excluded from LEED but could be incorporated as indicators.

### ***Methodology and organization***

To address the above-mentioned objectives, this research is divided into two main sections, the first includes an overview of the LEED system, as well as an in-depth analysis of its current regionalization strategies. Also, an implementation strategy for recommendations resulting from this investigation will be discussed.

This research will reference widely used **international SAS** such as **BREEAM**, **Sustainable Building (SB) Tool** and the **Living Building Challenge (LBC)**, its categories, indicators and weightings. A comparison between LEED and most recent versions of these SAS will inform what indicators may be added, modified or substituted to develop a revised LEED model for its specific socio-cultural context. Also, **localized** systems such as **Requirements for Sustainable Buildings in the Tropics (RESET)** in Costa Rica, **Green Mark** in Singapore and the **Green Rating for Integrated Habitat Assessment (GRIHA)** in India, that have emerged as a specific solution to the problems of a country or region within the tropics, will be discussed.

To analyse and compare the sustainability dimensions considered in the selected SAS, the second section includes a re-categorization of indicators that was developed as part of this investigation. Finally, contains a summary of social and cultural components deemed relevant for schools.

### **Leadership in Energy and Environmental Design (LEED)**

#### ***LEED overview and its implementation in Puerto Rico***

The US Green Building Council (USGBC) was established in 1993 by Rick Fedrizzi, David Gottfried and Mike Italiano (USGBC, 2016). LEED version 4 comprises a family of rating systems that address several building types in different stages of development (USGBC, 2016; Todd et al., 2013), that include Building Design and Construction, Operations and Maintenance, Interior Design and Construction, Neighbourhood Development and Homes.

Although LEED was designed in the United States and primarily reflects US market conditions, it has been used extensively around the world. As of July 2016, there are more than 161 countries and territories with LEED projects and over 33,500 certified commercial projects. Currently there are nearly 1,800 K-12 schools certified and over 2,000 registered (USGBC, 2016). Puerto Rico has the largest amount of LEED projects in the Caribbean region with a total of 47, out of which 9 are schools (19%). Additionally, 78 projects are labelled as “registered”, out of which 3 are schools (3.8%).

While most Green Building Councils in Latin America and Caribbean countries promote LEED as their main SAS, countries including Brazil (Selo Azul de Caixa), Mexico (PCES), Costa

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<sup>3</sup> Sustainability includes environmental, economic, social and cultural dimensions.

Rica (RESET) and US Virgin Islands (Green Building Certification) have developed their own SAS that incorporate socio cultural indicators in an attempt to address local needs.

### ***LEED section weightings, categories and credits***

LEED contains prerequisites and credits in nine (9) categories: Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation and Regional Priority (USGBC, 2016). To determine the LEED score, the total obtained in each criterion is added up, the maximum being 110 points. The number of credits achieved determines the project certification level as Certified, Silver, Gold or Platinum (the highest ranking) (USGBC, 2016).

The process to determine LEED v4 priorities and credit weightings, in order to target “social, environmental and economic goals”, was dedicated to answering this question: “**What should a LEED project accomplish?**” (Owens et.al., 2013:2,6). Hence, the LEED Steering Committee developed seven (7) weighted goals, namely: Climate change (35%), Health and well-being (20%), Water resources (15%), Material resources (10%), and Biodiversity (10%), while Economy (5%) and Social equity, environmental justice, and community quality of life (5%) were given the least percentage.

### ***LEED's Regionalization Strategies***

In order to improve global reach, several **regionalization strategies** such as Regional Priority Credits (RPCs), Alternate Compliance Paths (ACPs) and Pilot Credits, have been implemented.

#### ***Regional Priority Credits (RPCs)***

The **Regional Priority Credit** category, introduced in LEED 2009 allows project teams to earn bonus points by demonstrating compliance with the priority credits identified for a specific location. These credits, selected by the LEED International Roundtable and volunteers from green building chapters around the world, target environmental issues that affect their particular region or country (USGBC, 2016). Social, cultural and economic dimensions could not be considered because RPCs only recognize compliance of existing credits, and these are currently not included in LEED.

#### ***Alternative Compliance Paths***

In addition to RPC's **Alternative Compliance Paths (ACPs)**, attempt to adapt LEED to the local context and recognize differences in climatic conditions, codes, standards and laws applicable to projects outside the US (Horst, 2014). Even though projects in Puerto Rico can use some of these Global-ACP's (USGBC-FAQ), these would not be an effective strategy to locally adapt LEED considering that P.R. references U.S. standards and building codes. While overall consistency would be achieved, the recognition of local social, cultural and economic conditions in LEED indicators would need to be strengthened.

#### ***Pilot Credits and Innovation in Design Category***

Projects may pursue **Pilot Credits (PC)** within the **Innovation in Design Category**. This strategy allows teams to test criteria in the PC Library developed by others or submit new credits (USGBC, 2016). All proposals are then evaluated by the Pilot Credit Committee (PCC) and approved by the LEED Steering Committee (USGBC 2016).

An analysis of existing PC can give valuable insight about trends and new criteria proposed by project teams. For instance, most of the PC for LEED BD+C are related to the Materials and Resources category (33%), however a smaller percentage of credits (15%) belong to the Innovation category. It is relevant to acknowledge that within this category,

project teams proposed criteria that target social issues such as: (a) Social equity within the community and the project team, (b) Green training for contractors, trades and workers, (c) Integrative Process for Health Promotion, and (d) Prevention through Design.

The above-mentioned PC suggest an interest and need for LEED to target social aspects, however, there is no mention of any cultural aspects. As result, the USGBC's LEED Steering Committee created a Social Equity Working Group to improve the practical implementation of the above-mentioned Social Equity PC (USGBC 2016). Considering that the social and cultural sustainability dimension should be strengthened, the PC Library may be a valuable tool to propose new LEED criteria and test its effectiveness.

### **Proposed Implementation of Research Findings**

LEED regionalization strategies were analysed to determine the best approach to adapt the system for countries in tropical regions. In P.R., the USGBC local chapter, determined RPCs based solely on climatic and environmental conditions in the Island. Since Regional Priority credits were selected from existing indicators, no social or cultural factors were considered.

Out of the LEED Regionalization strategies, the innovation category could be a starting point to test the proposed indicators product from this research. Once approved by the USGBC and tested as PC, a Socio-cultural Working Group, under the LEED Steering Committee, could be developed by the USGBC to further develop these indicators, as it happened with Social Equity credits. Proposed PC could be used by other project teams within the Innovation in Design Category or could be incorporated into LEED as part of a new Socio-cultural Category. Green Building Chapters could then recognize social and cultural credits as critical and select them as Regional Priorities (see Figure 2).

### **International Comparison of School Sustainable Assessment Systems (SAS)**

This section will examine criteria in international and tropical SAS worldwide (BREEAM, Green Mark, GRIHA Prakriti, TERI GRIHA, LEED, LBC, RESET, SB Tool), to determine possible aspects missing in LEED and indicators that could be added into the system. The sustainability square, which includes the environmental, economic, social and cultural dimensions, was used as an initial reference for this analysis. A total of 8 certification systems and 779 indicators were added to a matrix, labelled according to the main issues identified; and regrouped into the following categories and subcategories, as shown in Figure 3 (Ebert 2011:21, Mateus and Bragança 2011:1962).

- **Building Technology and Environmental Impact:** Includes building and site considerations such as Infrastructure; Quality; Management; Efficiency; Material and Resource Availability (Sources); Consumption and Economic issues.
- **Design Criteria:** Includes indicators related to planning and spatial quality in buildings.
- **Social Needs and Integration:** Includes user related social and cultural aspects.

To further determine relevant sustainability cultural and social aspects that should be included in school SAS, a qualitative literature review analysis was developed. The study references work by several authors such as Walker (2014) and Axelsson, et al. (2013), that have developed cultural and social sustainability indicators and metrics to support design strategies and planning. Selected SAS manuals; documentation from the United Nations Education, Scientific and Cultural Organization's (UNESCO) proposal for Culture as the 4th Pillar of Sustainable Development in the Process of the Rio+20 Summit (Culture 21, 2011) and Culture for Development Indicators (United Nations, 2014) were also used as reference.

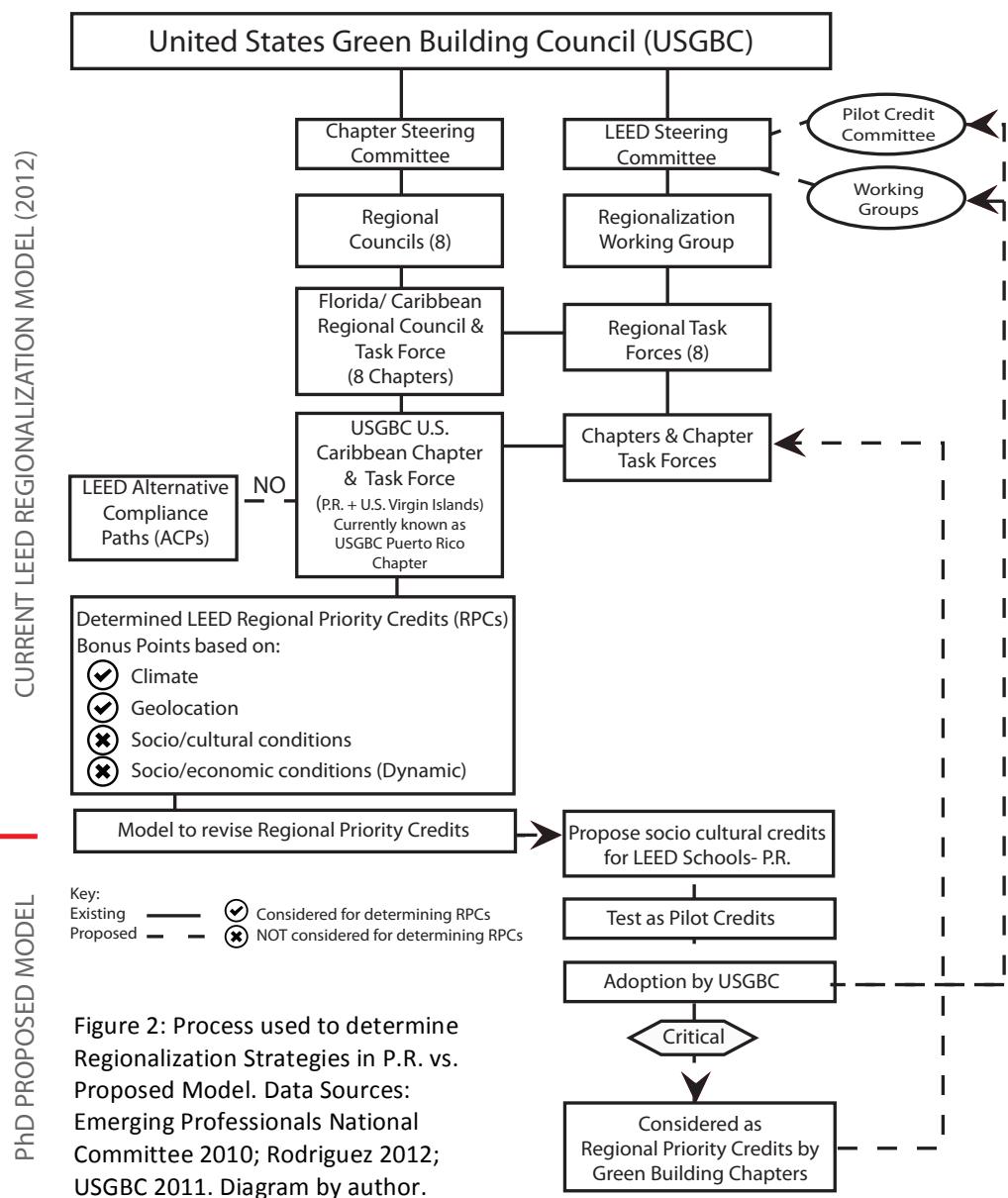


Figure 2: Process used to determine Regionalization Strategies in P.R. vs. Proposed Model. Data Sources: Emerging Professionals National Committee 2010; Rodriguez 2012; USGBC 2011. Diagram by author.

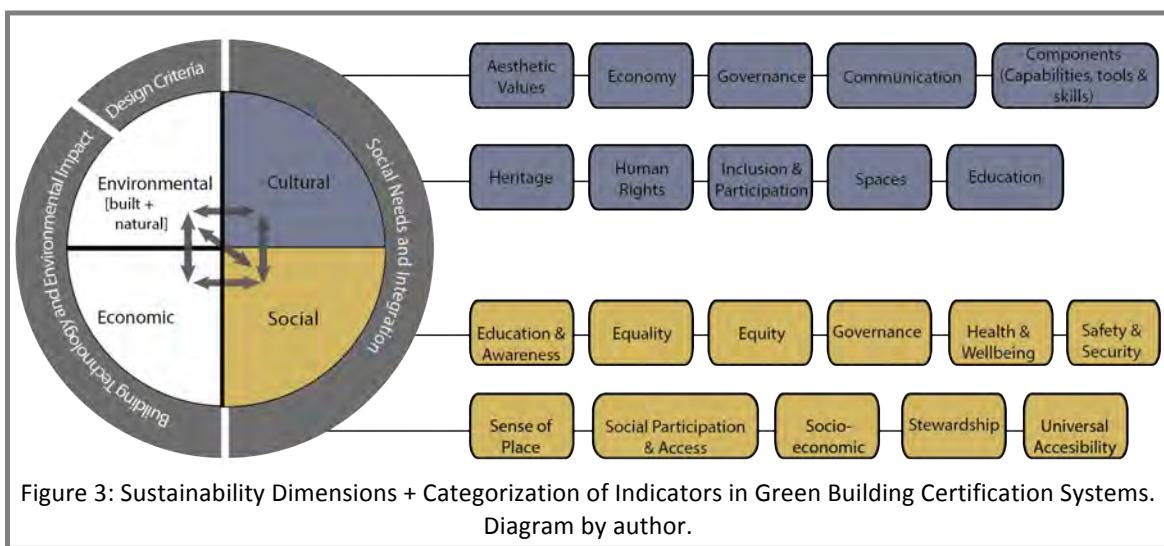


Figure 3: Sustainability Dimensions + Categorization of Indicators in Green Building Certification Systems. Diagram by author.

An analysis of previous studies suggest that cultural sustainability can be defined by the following components: Aesthetic values; Economy, Governance, Communication; Capabilities, tools and skills; Heritage; Human rights, Inclusion and participation; Cultural spaces; as well as Education, as shown in Figure 3 (Axelsson, R. et.al., 2013: 217; Culture 21 2011:1; Intl. Living Future Institute 2014: 59–60; UNESCO, 2014, 1989, 1972; UN, 2014:12; Walker, 2014:12).

While the term **culture** relates to the characteristics of a society or group of people, **social** relates to the “individual, family, or individuals in a society” and their interaction (Axelsson et al., 2013:215; Merriam-Webster, n.d.). Based on the literature review, **social sustainability** can be defined as a combination of the following components: Education and awareness; Equality; Equity; Governance; Health and well-being; Safety and security; Sense of place; Social participation and access; Socioeconomic; Stewardship, as well as Universal accessibility, as shown in Figure 3 (Aguilera et.al., 2006; Axelsson, R., et.al., 2013: 217-218; Diaz-Chavez, 2014:5, Gibberd, n.d.; GBC South Africa, 2014; “Sustainable socioeconomic development,” 2015; Government of Canada, 2010; Intl. Living Future Institute, 2014; Owens 2013:16; Energy and Resources Institute et al., 2014: 57-60; United Nations, 2014; Walker 2014:14; Wynhoven, n.d.).

Even though social and cultural indicators are included in the selected SAS (schools and others), not all components identified on the literature review and outlined on Figure 3 are considered by the certification systems analysed. Table 1 shows the components that are contemplated, the majority being socially related.

LEED's indicators, classified under the Social Needs & Integration category, for the purpose of this research, are mainly focused on Governance, Social participation and access, as well as the provision of Cultural Spaces. Other relevant indicators can be found under the PC library, as previously discussed, and are focused on Social equity, Education and awareness, Health, as well as Safety and security.

Table 1: Cultural and social components and indicators included in the selected SAS- Schools

Social and Cultural Sustainability Components in SAS					
Cultural Sustainability Components	Other systems	LEED Schools	Social Sustainability Components	Other systems	LEED Schools
Aesthetic values			Education and awareness		*
Cultural economy			Equality		
Cultural governance			Equity		*
Cultural communication			Governance		
Cultural components			Health & well-being		*
Cultural heritage			Safety & security		*
Culture and human rights			Sense of place		
Cultural inclusion & participation			Social participation & access		
Cultural spaces			Socioeconomic		
Cultural education			Stewardship		
			Universal accessibility		

**Key** The SAS includes all indicators identified in the literature review; \* Indicator included in LEED PC  
 Other Systems (Schools): BREEAM International In Use & NC 2016; Green Mark Existing Schools & New non-residential buildings 2015; GRIHA Prakriti Existing Schools; TERI GRIHA; LBC V3.0; RESET; SBTool 2015-16.  
 LEED for Schools: LEED V4 BD+C & O+M Schools

## Conclusions and future research

The discussion and findings of this paper will inform the overall objectives of the PhD. The sociocultural components identified will be further researched by developing a questionnaire to be administered to green design professionals and school directors. Results from this investigation could benefit LEED and SAS worldwide.

## References

- Anon., 2012. *ARRA- P.R.* [online]. Available at: <https://www2.pr.gov/> [Accessed 5.1.17].
- Axelsson, R., et al., 2013. Social and cultural sustainability. *AMBIO*, 42, 215–228.
- Brundtland, G.H., 1987. *Our common future: report for the WCED, United Nations*.
- Culture 21, 2011. *Lobbying for culture as the 4th pillar of sustainable development in the process of the Rio+20 Summit*. United Cities and Local Governments.
- Diaz-Chavez, R., 2014. Indicators for Socio-Economic Sustainability Assessment. In: Rutz, D. and Janssen, R. (Eds.), *Socio-Economic Impacts of Bioenergy Production*. Springer Intl. Publishing, Cham, 17–37.
- EPA, 2016. *Green Building /US EPA* [online]. Available at: <https://archive.epa.gov/> [Accessed 30.12.16].
- Fielding Nair Intl., n.d. *Schools for the 21st century: Setting a new global standard for excellence*. P.R.: AFI.
- Gibberd, J., n.d. *Sustainable building assessment tool residential design (SBAT) 1.04*. Gauge.
- GBC South Africa, 2014. *Technical manual Green Star SA: Socio economic category pilot*. GBC South Africa.
- Horst, S., 2014. *ACPs continue to localize LEED* [online]. Available at: <http://www.usgbc.org/> [Accessed 17.2.16].
- Instituto de Estadísticas de P.R., 2014. Anuario Estadístico del Sistema Educativo 2011-12. P.R.: IEPR.
- Intl. Living Future Institute, 2014. Living Building Challenge [online]. Available at: <https://living-future.org/lbc/>
- Mateus, R. and Bragança, L., 2011. Sustainability assessment and rating of buildings: Developing the methodology. *Building and Environment*, 46, 1962–1971.
- Merriam-Webster, n.d. *Definition of Social* [online]. Available at: <https://www.merriam-webster.com/dictionary/social> [Accessed 27.3.17].
- Office of the Federal Environmental Executive, n.d. *The federal commitment to green building: Experiences and expectations*. [online]. Available at: <https://obamawhitehouse.archives.gov>
- Owens, B., et al. 2013. *LEED v4 Impact Category and Point Allocation Process Overview*. USGBC.
- Rodriguez, C., 2012. *Regionalization 2012*. San Juan: U.S. Caribbean Chapter.
- Eurostat, 2015. *Sustainable Socioeconomic development* [online]. Available at: <http://ec.europa.eu/eurostat/statistics-explained/index.php> [Accessed 3.2.17].
- The Energy and Resources Institute, Association for Development and Research of Sustainable Habitats, 2014. *GRIHA Prakriti rating for existing day schools manual* (Pilot V. 1.0). India: GRIHA Council.
- Todd, J., Pyke, C. and Tufts, R., 2013. Implications of trends in LEED usage. *BRI*, 41, 384–400.
- UIA, 2012. *RESET: Requirements for sustainable building in the tropics*. Costa Rica.
- UNESCO, 2014. *Basic texts of the 2003 Convention for the Safeguarding of the Intangible Cultural Heritage*. France: UNESCO.
- UNESCO, 1989. Draft Medium-term plan, 1990-1995. In: *General Conference, 25th Session*, Paris, France, 17 October - 16 November 1989. Paris: UNESCO.
- UNESCO, 1972. Convention concerning the protection of the world cultural and natural heritage. In: *General Conference, 17th Session*, Paris, France, 17 October - 21 November 1972. Paris: UNESCO.
- United Cities and Local Gov., 2010. Culture: Fourth pillar of sustainable development. Barcelona: UCLG.
- United Cities and Local Gov., 2008. *Agenda 21 for culture*. Barcelona: UCLG.
- United Nations, 2014. *UNESCO Culture for development indicators: Methodology manual*. Paris: UNESCO.
- U.S. Department of Education, 2009. *School Modernization* [online]. Available at: <http://www2.ed.gov/policy/gen/leg/recovery/modernization/index.html> [Accessed 28.12.16].
- U.S. Senate, 2008. Congressional Record. In: *110th Congress Second Session*. Washington D.C., 22098–22099.
- USGBC, 2016. *U.S. Green Building Council* [online]. Available at: <http://www.usgbc.org/> [Accessed 5.1.17].
- USGBC, 2011. *Introduction to LEED Regionalization* [online]. Available at: <http://www.usgbc-illinois.org/> [Accessed 30.4.2016].
- USGBC, 2010. *Emerging Professionals local leaders toolkit* [online]. Available at: <http://www.usgbc.org>
- Walker, E., 2014. *Exploring socio-cultural dimensions of sustainability*. MLA thesis, University of Maryland.
- Wynhoven, U., n.d. *Social sustainability* [online]. U. N. Glob. Compact. Available at: <https://www.unglobalcompact.org/what-is-gc/our-work/social> [Accessed 3.1.17].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Zero-Energy Me - The Struggle for Individual Energy Neutrality

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**Abstract:** The strife for zero-energy buildings and carbon-neutral developments is – however noble and benevolent – mostly aimed at an abstract target, such as a design in architecture school, a house still to be built, an urban plan under development. It is mostly dealing with there, then and them, rather than here, now and us. A sustainable, climate-, carbon- or energy-neutral society implies that each individual needs to be sustainable, climate- or carbon-neutral. Acknowledging this, the main author started to keep track of his performance in energy use, travel and food habits, and during lectures he presented about this openly to his students. Over a period of 7 years, the detailed tracking of energy, travel and food, and, more so, consecutive actions taken, have led to a lower energy consumption and hence carbon footprint. In the author's private life, we should say, because in the meantime his professional international career took off and so had many flights across the globe. They once more demonstrated that we, even when living low-carbon consciously, often are penny-wise, pound-foolish. This individual research clarified the greatest challenges and most effective strategies of living in a modern, dense city, with abundant access to unsustainable food and with easy opportunities to travel unsustainably for little money. As it held a mirror to the author, it will do too to a greater audience.

**Keywords:** net zero-energy, carbon neutrality, accommodation, transportation, food

### Introduction

If we want to stay beneath a 2-degrees temperature increase – widely considered a maximum level to avoid runaway climate change with unpredictable outcome - the world needs to reduce its carbon emissions by 80% in the year 2050 [IPCC 2014]. For a sustainable situation on the longer term, climate neutrality or carbon neutrality is essential, creating a balance between the greenhouse gases emitted on the one hand and chemically binding or sequestering of these gases on the other.

### Society's great energy challenge

The predominant part of achieving this goal, as agreed upon in the Paris treaty of 2015, is to be achieved by becoming independent from fossil fuels, the greatest contributor to greenhouse gases as methane, CO<sub>2</sub> and NOx. Therefore, the term 'fossil free' was introduced in various European projects already since 2006 [e.g. Roggema et al. 2011], after Al Gore's 'An Inconvenient Truth' came out [Gore 2006]. Fossil free simply means that no fossil fuels (coal, mineral oil and natural gas) are used anywhere in the system considered. With our fossil society this is an ambitious goal to achieve, and it may take a lot of time to get there. In the meantime, becoming 'net zero-energy' already is a big step. This ambition, often also described as 'energy-neutral', means that in a year's time one is not to use more energy than one can generate oneself. It implies acceptance of fossil fuels as long as this quantity of energy

is compensated for by self-generated renewable energy. In its Energy Performance for Buildings Decree (EPBD), the EU prescribes that as of 2020 all new buildings need to be ‘nearly zero-energy’. The word ‘nearly’ of course leaves space for interpretation, but it is clear that designing fully zero-energy buildings will put architects on the safe side for a building permit.

### ***Individual energy-neutrality***

The strife for zero-energy buildings and carbon-neutral development is noble and benevolent for future generations to follow. However, it is usually aimed at an abstract target, such as the design of a building in architecture school, a house still to be built, an urban plan under development. It is mostly dealing with there, then and them, rather than here, now and us. A sustainable, energy- or carbon-neutral society will not be possible if people themselves on average are not sustainable, climate-adaptive, carbon-neutral in their own way of living. It is easy to point at others and not achieving these goals oneself. People who understand the importance of striving for a sustainable world, must set the example by becoming net zero-energy in their habits. Acknowledging this, the main author started to keep track of his performance in energy use, and during lectures he presented about this openly to his students. This paper gives an account for the measurements and calculations done in the period of 2010-2016.

### **Boundary conditions and starting-points**

#### ***Sources of energy use considered and unconsidered***

Energy neutrality may be considered for many parts of our lives.

Perhaps most trivial is the energy used at home, including building-related energy (for lighting, heating, ventilation, pumps etc.), user-related energy (for use of equipment, devices, lifts etc.), and also the ‘embodied energy’ of building materials (for winning, transport, production etc.). The latter we usually do not consider because we usually do not have data thereof.

Other forms of energy use are related to our own living: mobility (private travel, commuter travel etc.), water (energy needed for producing drinking water, for pumps, for the purification of waste water, etc.), food (energy needed for growth, transport, storage and production of food), clothes (energy needed for the resources, transport and production of clothes), stuff (energy needed for the resources, transport and production of stuff), and again, the embodied energy of packaging and materials of previous products.

Least obvious, yet an essential part of everyone’s life is the (embodied) energy use of everything we use outside ourselves: infrastructure (roads, bridges, piping, wiring, sewage, etc.), utilities and facilities (for electricity, drinking water, waste water treatment, etc.), public objects (public buildings, street furniture, etc.), commercial objects (factories, offices, retail, etc.), and so on.

For practical reasons this research was limited to the building-related and user-related energy at home, mobility and food. Based on estimates that around 30-40% of carbon emissions result from the built environment (buildings) and 20-30% from transportation, the authors assume that thereby they have covered over half the energy individuals use, at least a part they can influence.

## **Method**

Over a period of 7 years the main author's energy use and travel was tracked in detail, linked to annual energy bills. Since the main author moved house in December 2009, with a baseline measurement done, account was made on the 1<sup>st</sup> of January every year. 2010 was the reference year, with little to no adjustments made to the house, after which various consecutive measures were taken and their effect measured.

Next to this private part of life, a professional career defines the use of energy; also with the individual considered. Working in an office most of the time, the energy consumed at the office is important but has to be divided by all who use it. Business travel can be an even more decisive factor. In the case of the authors this is certainly true, reason for which to keep track of business trips, both by car, train and plane.

## **Basics of energy**

Repetition of some figures is useful before we present energy data in the section to come. For conversion to a general energy value only two conversion factors are relevant (actually only one): 1 kWh = 3.6 MJ; and 1 MJ = 0.278 kWh. Besides, the energy content of common energy sources is important. Table 1 gives an overview of this. Notice that all fossil fuels as well as biotic oil and fat have an energy content of around 36 MJ i.e. 10 kWh per unit.

Table 1. Energy sources and energy content per unit

<b>Energy source</b>	<b>Unit</b>	<b>Energy content</b>	
Natural gas	1 m <sup>3</sup> nge (natural gas equivalent)	35.2 MJ	9.8 kWh
Petrol	1 l (litre)	32.4 MJ	9.0 kWh
Diesel	1 l	35.8 MJ	10.0 kWh
Kerosine	1 l	37.4 MJ	10.4 kWh
Oil and fat	1 kg vegetable/animal	37.0 MJ	10.3 kWh
LPG	1 m <sup>3</sup>	26.0 MJ	7.2 kWh
Coal	1 kg	24.0 MJ	6.7 kWh

Related to the energy mix of electricity the Netherlands has an average efficiency of around 45%, which implies – unless one uses electricity from renewable sources – we have to multiply the use of electricity by 2.2, in order to get to the amount of primary energy.

Furthermore, note that one flame (either a flame of a candle, oil lamp or gas burner) has a heat power of around 100 W [Hermans 2011]. Gas boilers and geysers often used to have ten rows of ten gas flames, giving them a heat power of 10 kW. One flame burning one hour long has produced  $100 \times 1 = 100$  Wh (watt-hour). Someone taking a shower for 15 minutes has used  $10,000 \times 0.25 = 2,500$  Wh or 2.5 kWh. Taking an efficiency of 100%, this is the equivalent of 0.25 m<sup>3</sup> of gas, or 250 ml ('a longdrink glass') of petrol.

## **Local energy habits**

In the Netherlands, the main author's home country, inhabitants typically have access to electricity, natural gas, drinking water, sewage, and other utilities that are centrally provided by public or private service companies. Recently, there is a shift towards dwellings free of natural gas, but the large majority of the building stock still relies on it (for both heating and hot water). Cars mostly use petrol or diesel, and airplanes kerosene. Electricity comes from centralised, regional power plants, which run on natural gas, coal or a small share of biomass. In North-Western Europe electricity is not bound to country borders and some of the energy produced in the Netherlands is exported while a small amount of nuclear power is imported from Belgium or France. The Netherlands are positioned second to last on the European table

of renewable energy (a share of around 5%) [Eurostat 2016]. So the energy mix is diverse, with dominance of natural gas.

### ***Energy use of Dutch households***

For their house, Dutch households on average use 1,400 m<sup>3</sup> of gas (13.6 MWh thermal) and 3,500 kWh (7.7 MWh of primary energy). In total this is 21.3 MWh<sub>prim</sub> (76.7 GJ). Ignoring public transport and bikes, for their mobility the Dutch drive on average 13,300 km per year. With 8 l/100 km this is around a thousand litre of diesel or petrol, or 36 GJ or 10 MWh<sub>prim</sub>. Hence, for living and private travel the total energy demand of a Dutch household is 31.3 MWh<sub>prim</sub>. Households on average contain 2.2 persons [CBS], so the individual energy use is 14.2 MWh<sub>prim</sub>. This is nearly 30% of the total energy the Netherlands used in the year 2015: 49.9 MWh per inhabitant [PBL 2017]. The private use of energy requires a continuous power of 3.56 kW, of which 2.43 kW for the house.

## **Domestic energy consumption**

### ***Energy system of the house***

The terraced house under scrutiny is positioned in the inner-city of Delft, the Netherlands. Officially it is an apartment, squeezed in between two neighbours and a cinema at the back, with shops underneath and a parking garage below these. It therefore has an uncommon wide and shallow floor plan, with one open façade. Total gross floor area is 165 m<sup>2</sup>, with approximately 460 m<sup>3</sup> of space. The house is inhabited by a family of four: two parents and two teenage children.

The multifunctional urban complex the house is part of was delivered in 2005. Compliant with the energy codes of that time it has HR+/HR++ windows ( $U = 1.0\text{-}1.3 \text{ W/m}^2\text{K}$ ) and, compared to the Dutch average, good thermal insulation ( $R_c = 3.0 \text{ m}^2\text{K/W}$ ). For energy-efficient ventilation the house has so-called balanced ventilation with heat recovery, which can be switched to three speeds; filters for incoming and outgoing air need to be regularly replaced by the house owner. The complex has a shared heat-pump system that is connected to a collector of tubes that exchange heat with the underground. The heat extracted from the soil pre-heats warm water used for floor heating and hot water. For hot water (used in the bathroom) it needs to be electrically after-heated in a boiler tank. The house's kitchen contains small electric close-in boilers, one for boiling water, one for normal hot water from the tap.



### ***Energy use in 2010, the reference year***

After a year of use and only minor adjustments (replacing broke lightbulbs with more energy-efficient ones, the energy use measured was:

- Electricity 5,622 kWh
- Heat 36 GJ heat (from the heat-pump system)
- Total 56 GJ or 15.6 MWh

The total energy use come down to 1.77 kW of permanent power (in this case fully electric). This is already 27% less than the Dutch average house. So although the consumption of electricity is higher than average, the use of heat from a heat pump is so much lower than the usual use of gas, that the house could be called energy-efficient already.

### ***Measures taken since 2010***

Since 2010, all lighting has been replaced by LED and energy-saving fluorescent lighting. Based on calculation of sufficient levels of fresh air for a family of four, standard ventilation rates were brought down from 50 to 20% of full power, which also reduced noise levels indoors. The boiler temperature was reduced from 65 to 55°C, a level that safe enough against Legionella bacteria with short piping circuits. In August 2011, 5 m<sup>2</sup> of mono-crystalline PV was installed on the small flat roof of the house (15%, 550 W<sub>peak</sub> ~ 600 kWh/a). As a measure of effective flexible thermal insulation during winter evenings and nights, in November 2011 thick curtains were hung behind the large windows of the second floor. As a technical measure to fix the floor heating system, a much more energy-efficient water pump (from hundreds of Watts to 10 W on average) was installed in early 2013. Finally, and not unimportantly, the residents switched off boilers and electrical equipment when they were away for at least two days.

### ***Energy use since 2010***

Table 2 gives values for energy use figures, measured between 2010 and 2016. All values have been converted to 365 days, and heat values were calibrated according to degree days.

Table 2. Energy sources and energy content per unit

Date	Electricity	Savings	Heat	Savings	Total	Permanent	Savings
02-10-2011	4,676 kWh	17%	36.0 GJ		56 GJ / 15.6 MWh	1.77 kW	
31-10-2012	4,338 kWh	23%	25.6 GJ	29%	42 GJ / 11.8 MWh	1.35 kW	24%
16-11-2013	3,946 kWh	30%	74.7 GJ*	-108%	89 GJ / 24.7 MWh	1.82 kW	-56%
08-11-2014	3,822 kWh	32%	28.9 GJ	20%	43 GJ / 11.9 MWh	1.36 kW	24%
07-11-2015	3,739 kWh	33%	24.3 GJ	21%	38 GJ / 10.5 MWh	1.20 kW	26%

\* In 2013 a very odd measurement was done by an official of the energy company. Although no fraud by the official could be proven, the energy company returned the extra costs of 2013 in the years after, when the dwellers had proved the falseness. So this measurement can be ignored.

Converting the results of Table 2 to the main author only, taking the two kids as one adult, the personal use after these years of savings turns out to be 12.6 GJ or 3.5 MWh, 400 W permanent. This is 55% less than the average Dutch person. For this use of electric energy renewable power is purchased off an organic farmer with PV on his stables, via energy company Vandebron (literally ‘from the source’). So the house considered is not energy-neutral – it does not produce all of its own energy – but it is carbon neutral – all energy it uses is from renewable sources.

### ***Further savings***

Following the New Stepped Strategy [Dobbelsteen 2008], further reuse of waste heat (step 2) is difficult since heat from exhaust air is already recovered and installing heat recovery systems on waste water from the shower and bath is practically impossible.

That leaves the following measures for reducing the energy demand (step 1) still to be taken: achieving better airtightness by foam strips (executed in the winter of 2016), applying curtains in all rooms (still to be done), and using external sun-shading (see next).

A greater production of renewables (step 3) could be achieved by a solar collector, but in combination with the heat pump system already installed, the added value is very limited, and extra expenses disproportional. Adding more PV is only possible on the facades, for which approval is necessary of the house owners' society and municipal architectural committee. More interesting would be to combine external sun-shading with PV strips (louvres) on the south façade next to the roof terrace (a big source of undesired heat in summer). This is currently explored. Adding a small wind turbine next to the PV on the upper roof (for instance the Windleaf, by Windchallenge) is spatially possible but with a projected annual yield of around 800 kWh and an investment of more than 3000 euro, return on investment still takes about 20 years. It is however considered seriously.

It appears, as with many dwellings in dense inner-city locations, possibilities for personal production of renewable energy (and hence, becoming net-zero energy) is limited, leaving the sustainable procurement as a good option.

### **Personal transportation and commuter travel**

#### ***Situation before and after 1 January 2010***

In December 2009 the main author, following his appointment as full professor at TU Delft, moved from Amsterdam to Delft, changing his modal split from riding the train and cycling to and from stations to cycling directly to his faculty building. Regardless of this commuter transport there of course also is personal transport, which will be elaborated shortly here.

#### ***Cycling and walking***

Cycling costs approximately 60 kJ/km (per person). Energy for this comes from food. Before 2010, the main author cycled 5 days a week, 10 km a day, which comes down to 2,300 km a year. In energy this equals 138 MJ. After 2010 the cycling distance halved to a maximum of 5 km a day, 5 days a week, entailing an energy use of 79 MJ.

#### ***Public transport: train rides***

Trains use 80 Wh/p.km of electricity, based on average occupancies in Dutch trains. Before 2010 for his commuter transport the main author travelled 5 days a week over a distance of 72 km, a total annual distance of 33,000 km. The electric energy needed for this was 2600 kWh (9.36 GJ). After 2010 this dropped to an average of train business trips of 80 km a week, a total annual distance of 3,700 km. This implies an energy use of 294 kWh (1.06 GJ), 90% saved.

#### ***Private car use***

The main author has a private car, a Volkswagen Transporter T4 camper van with Transfalia infill. It has a 2.4-litre diesel engine, and it uses one litre for 11 kilometres on average. Hardly energy-efficient but seldomly used and a sustainable means of combining travelling with holidays on campsites in summer. The car is used for the whole family, two adults and two teens, which we count as 3 persons, so the individual share for the main author is one third.

Before 2010 the main author used the car for 12,000 km a year, using 1,090 l of diesel, which equals 36,3 GJ. Divided by three this means a personal use of 12.1 GJ. After 2010 care use dropped to 9,000 km a year, implying a use of 750 l of diesel with the energetic equivalent of 27,3 GJ. The main author's personal use therefore is 9.1 GJ.

### **Conclusion**

Seeing the figures for transportation one noticed the big difference of energy used for cycling, riding trains and driving cars. The car, even with a smaller distance covered than the train uses by far the most energy per person. For the main author's private travel the total energy use went from 21.6 GJ in 2010, to 10.2 GJ (2.8 MWh) after that year, an energy saving of 53%.

Since 2017 the Dutch railways ride on 100% of renewable energy (wind power) after one year of 50% of renewables. So the only real problem to become carbon neutral is the main-author's diesel-fuelled car, with a share of 41% of his total energy use, including the house.

### **Other factors of individual energy**

#### ***Business travel and the energy of flying***

Based on energy data of air travel the main author has kept track of his business trips since 2011, consisting of train rides in the Netherlands and neighbouring countries (Belgium, Germany, UK), some distances covered by car and flights. The energy use of airplanes strongly relies on the distance covered, the airplane itself and the occupancy.

Based on the distance and mode of transport, 2011 showed a relatively modest energy use of 3.2 MWh (11.5 GJ), 90% of the personal use of energy for the house. 2012 saw 3 intercontinental flights and 3 continental flights, which led to a total energy use of 47.6 MWh (171 GJ), seven times more than the energy used for house and personal travel. In 2013 business travel reduced to 42.7 MWh (154 GJ), in 2014 to 32.6 MWh (115 GJ), but thanks to the success of European research projects and international collaboration the energy consumed for business trips in 2015 and 2016 was greater than 50 MWh.

#### ***The energy of food***

As already introduced, food is an important factor for energy consumption. The term of 'food miles' indicates the distance that food has to travel to arrive in the supermarket; also the means of transport and necessity of frozen or chilled storage plays an important factor. Not to forget the production of food in greenhouses, under optimised conditions, requiring heating in winter, to mention one aspect. Meat and fish cost more energy than other foods; meat is the killer when considering greenhouse gas emissions [[www.landshare.org](http://www.landshare.org)]. So becoming energy-efficient and low-carbon requires a conscious lifestyle that includes wise selection of food. The authors made a calculation of average eating patterns and compared these to vegetarians or vegans, which made a big difference when taking an American lifestyle as the basis [US Department of Agriculture] and less so when looking at a continental European [RIVM]. In general, eating seasonally fitting food avoids a lot of energy for transport and storage. Most effective is eating less meat.

#### ***Other sources of individual energy use, not assessed***

There are many more elements of life that cost energy and that have not been assessed for this paper. For instance, pumping out rainwater, producing drinking water and processing wastewater all cost energy. Furthermore, the extraction, transport and processing of resources requires energy that can be considered as 'embodied energy' of materials and

products. A particular kind of products are clothes and what we may call stuff. Almost impossible to assess all of these, they form a part of everyone's life and choices, hence have an important influence on the environment.

## Conclusion

In total, in the year 2015, the individual considered used 22,8 GJ or 6,3 MWh for his house and personal travel. This is 41% less than the reference year and 49% less than the average Dutchman. The actions taken by the main author clearly led to a lower footprint. Of the energy used, 60% is carbon-neutral, the diesel van being the main problem to be solved. Net-zero energy living is possible but difficult when considering dense urban circumstances, but everyone can be carbon neutral when energy is procured from renewable sources. For mobility, unless one can fully use human-powered or public transport, becoming energy- and carbon-neutral is more of a challenge, and this particularly holds true for flying. The calculation of energy for flying goes to show that painstaking efforts to reduce the energy used at home to carbon-neutral and nearly zero-energy are terrifically over-compensated when flying for business (or for private goals).

If all energy used at work were to be accounted to employees, we would have to include many more sources of energy use: the office, ancillary company utilities, the conference for which this paper was written... Perhaps all of these factors should be included. After all, in the near future we will all have a carbon budget that cannot be exceeded, produced at home or at work does not matter then. Therefore, one of the next steps is to convert all energy use related to the university to all of its employees and students. Including these factors will increase the individual influence one can have on the national energy use from 30 to at least 50%.

This individual research clarified the greatest challenges and most effective strategies of living in a modern, dense city, with abundant access to unsustainable food and with easy opportunities to travel unsustainably for little money. As it held a mirror before the author, it will hopefully do as well before a greater audience.

## References

- Dobbelsteen A. van den; 'Towards closed cycles - New strategy steps inspired by the Cradle to Cradle approach', in: Proceedings PLEA 2008; UCD, Dublin, 2008
- Gore A.; *An Inconvenient Truth - The Planetary Emergency of Global Warming and What We Can Do About It*; Rodale, New York, USA, 2006
- Hermans J.; *Energy Survival Guide*; Leiden University Press, 2011
- IPCC (Intergovernmental Panel on Climate Change); *Climate Change 2014: Impacts, Adaptation, and Vulnerability*; IPCC, Switzerland, 2014
- PBL (Planbureau voor de Leefomgeving); 'Aanbod en verbruik van energiedragers in Nederland, 2015', URL: <http://www.clo.nl/indicatoren/nl0053-energiebalans-nederland-tabel>; Compendium voor de Leefomgeving, 2017
- Roggema R., Dobbelsteen A. van den, Stremke S. & Mallon W.; 'Spatial Energy Framework Aiming at Breakthroughs Brings Goals beyond Policy Objectives within Reach', in: Jenkins A.L. (ed.), *Climate Change Adaptation* (127-150); Nova Science Publishers, 2011



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Cognitive mapping as a link between the urban designer and space user

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**Abstract:** The Visual Identity of open spaces results from our cognitive image. This can be the result of both physical and non-physical ties to the landscape change. It affects users' perception and provokes their senses. Recent researchers revealed there is a gap between the intended design developed by the urban designer and the users' cognitive map of the space. The research aims to determine the most important factors that the urban designer should keep into consideration to reduce this gap. The research used semi-structured interviews & mapping tool to analyse the landscape change over the past 10 years for open space food courts in three new residential communities in Egypt. The result presents a comparison between the three perspectives for landscape change; 1) theoretical guidelines for designing urban space elements, 2) urban designer's design approach and 3) users' cognitive map for open spaces. This method can be used to convey, share and exchange information for landscape designers, urban planners and decision makers.

**Keywords:** Cognitive map, Cognition, Landscape Change, open Space.

### Introduction

Human cognition is a reflection of what is processed in memory as a result of the perception of featured elements and experiences. This is developed into knowledge and understanding of the surrounding context and includes processes of reasoning and judgment (Adams & Aizawa, 2010; Lewandowsky et al., 2012). It depends on a set of physical and psychological factors. The former constitute factors related to the design of space elements, while the later constitute factors related to users' age, sex, metabolic activity, culture and occupation (Berto, 2005). Yet, few studies have provided an empirical basis to consider the use of cognitive maps in designing open spaces in Egypt (Marwa Adel El Sayed and Ayman Mahmoud Hassan, 2015). This contradicts with the poor knowledge that urban designers and landscapers have about users' cognitive map (Marwa Adel El Sayed and Ayman Mahmoud Hassan, 2015)

The study is divided into two parts with ten years apart. It aims at comparing the principles of landscape design change through the main cognitive factors indicated in the first part of the study for open space food courts. According to Oxford dictionary, Food court is defined as the area in a shopping mall where fast-food outlets are located. The study uses analytical methods and techniques to structure and display the case study data. It also uses structured interviews to characterise users' cognition towards open space design.

### Literature review

Previous studies have attempted to understand the relationships between landscape characters and how this affects visual perception. Some studies used statistical analysis such

as multivariate analysis, cluster analysis (Hagerhall, 2000; Hoffmann-Kroll et al., 2003; Ruiz & Domon, 2009), photographs and interviews (Polat & Akay, 2015; Nitavská, 2011).

### **Landscape features as a Communication language**

Brown & Brabyn (2012) stated that understanding and managing landscape values require investigating a common set of terminology for landscape interpretation (Brown & Brabyn, 2012). Some studies have pointed the need to have a classification of landscape characters to develop a common language of visual vocabulary and act as a reference for communication at the most basic structural, perceptual and aesthetic levels (Atik et al., 2016; Brabyn, 1996). This includes cultural features, aesthetic features and value features and elements. This develops the distinct and recognisable character of landscape design based on common vocabulary and language of particular features and values (Swanson, 2002; Turner, 2006; Jessel, 2006). Hence, characterization is developed into communication through conceptual grounds of objective, subjective and interpretive cluster analysis (Caspersen, 2009).

### ***Space change, interaction & multi-functionality; Forces of change and interaction***

Quinn & Bhatt (2012) stated pinpointed that our perception of our environmental is influenced by both temporal and spatial factors (Quinn & Bhatt, 2012). According to Palang et al, (2000), understanding landscape change can be used to draw prediction scenarios for the visible, material changes. Such scenarios should create the transitional link between the past and future trends in landscape design (Palang et al., 2000). Landscape component and value is composed of both individual elements and landscapes as a whole, and that the former is only meaningful when perceived within the whole landscape context (Antrop, 1997; Naveh, 2000). This requires methods of exploring the divergent methods of understanding, evaluation and goals which caused the change, and motives of different stakeholders which could affect their role in managing landscape change (Marcucci, 2000). It also requires methods of monitoring, evaluating and managing change through both quantitative and qualitative analysis such as the landscape impact analysis method (Emmelin, 1996).

### **Methodology**

This study targets outdoor food court spaces as recently introduced amenity areas in the Egyptian context. The paper adopts an analytical comparative approach that uses both the tools of data collection and data analysis. These tools allow an approach that is structured based on cognition science. Both qualitative and quantitative data have been compromised in the research. The tools of the qualitative data are built on literature review and collecting deferent methods of thematic cognition. The tools of quantitative data are mainly built on site observations, structured interviews, and structured questionnaires. Ten percent of the space peek daily users have been interviewed. Hence a number of 210 users were interviewed in Rehab food court, 250 users were interviewed in Safari food court, and finally 200 users were interviewed in the district food court. The users have been divided according to the gender (male, and female) and each are divided into three age groups. The first age group ranges from 18 to 40, the second ranges from 40 to 60, and finally the third over 60. Through the designed questionnaire and the structured interviews three main aspects were measured. It starts by investigating the elements that enhance users' perception through internal and external factors. The former is based on the users' grounding experience and the latter is related to material of the surrounding space. Then it is followed by studying the elements that enhance the users' cognition processes. Those elements are divided into age, sex, culture,

and previous experience for the users. Finally it considers the demands for both the outdoor environment and outdoor activities that support forming an identical cognitive map.

The study aims at investigating the effect of time on landscape design principles and how this affect users' cognitive map in outdoor food court areas. It is divided into two parts carried with 10 years difference. Ten main criteria were deducted from part one of the study as a result of a comparison between urban design theories state, users' perception, and urban designer's intended design. Part two of the study tests the effect of time on landscape change in terms of these criteria.

### **Part one (March 2007)**

This part aimed at investigating users' perception which is developed into individual preferences. The study used structured questionnaires, structured interviews, and site observations. The practical field study was completed for two food courts; Safari Zone food court and El Rehab food court. The former covered a wide service area due to its location lying along the main spine of Cairo-Alexandria within a business, commercial, craft context. Its unique location is considered an attracting destination for Cairo citizens; the food court size was one (100 meters \* 10 meters). The later was located along Cairo El-Suez road surrounded by a residential compound, which mainly serves Rehab, Nasr city, and Heliopolis residents. The food court size was one hundred and (80 meters \* 50 meters) as shown in Figure 1.

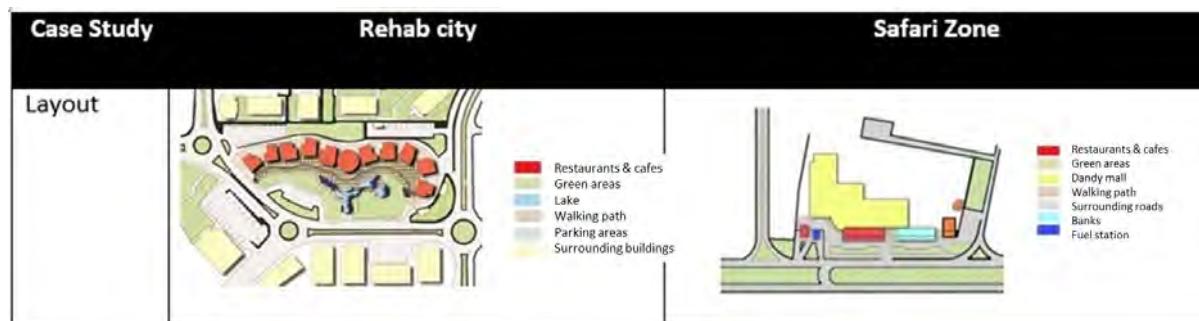


Figure 1. The layout of the two food courts

The study highlighted seven principles for urban and landscape design, those are; size, enclosure, entrances, boundaries, furnishing, Morphology of surrounding building and pedestrian safety. This is in addition to three factors that aid to provoke cognitive image using senses, those are; landmark, paths and unobstructed view.

Conferring to different urban concepts and theories, Lynch (1960) has recommended that the optimal size of an urban space varies from 24m to 137m, and Gehl (2011) proposed that it should not go beyond 100 m (Lynch 1960; Gehl 2011). Users' sense of enclosure is enhanced when the ratio between the vertical and horizontal planes is 1:2 or 1:3 respectively. If the ratio goes down to one-fourth or less, the users start to lack the enclosure sense of the space. The urban space entrance should be visible and welcoming to users and exposed to public right of ways. As for space furnishing, the open-air sitting is divided into two categories, the first category is sitting benches that are preferred to be placed one m linear of seating for each nine square meters, and the second category considers walls with height forty-five meters that may be with or without a handrail. According to the law of Gestalt of simplicity continuity and similarity of form, Morphology of surrounding building can be perceived more easily than other complex buildings (Jäkel et al., 2016). Pedestrian safety is improved through elimination or reduction of vehicle and pedestrian conflicts throughout separation of space,

either vertical or horizontal, or via time separation. Additionally, provoking cognitive image using senses should be achieved using more identifiable landmarks with a clear form and contrast with the background. The placement bed of the path should be finished from one type, to provide a sense of continuity to the observer. The path width should follow the following equation Path width = V (M) / S. Unobstructed forward view for pedestrians for walking is 10.6 m plus (Huang et al., 2014).

Table 1 presents the results of the comparison and the researchers' observations. The green colour indicates the matching of views and the red colour indicates a conflict of views.

Table 1. Shows the results of part 1 of the study

Urban Space	Theory	Reality	Users	Researchers' observations
<b>Space size</b>				
Rehab				Not only is the space size that gives the users a sense of relief and content, but it related to the surrounding urban morphology. This includes the height and arrangement of surrounding buildings inside the space. Space size may be the same but users' perception may change depending on urban morphology. This may consequently reflect on their feeling of safety, containment and relief inside the space.
Safari			Red	
<b>Space Enclosure</b>				
Rehab				Users' feeling of safety in urban spaces is enhanced by reduction or elimination of vehicle circulation crossing with users' circulation. This can be done physically through horizontal and/or vertical separation, and it can be done through time separation as well. It is important to note that the larger the street width, the more separation is required.
Safari			Red	
<b>Entrances</b>				
Rehab		Red		The food courts' entrances provide a welcoming approach for many users. This is the case in the Rehab food court, the entrance is facing the stairs path of the parking lot, and the entrance of Safari is located along the path of the parking lot.
Safari		Red		
<b>Space boundaries</b>				
Rehab	Red			Space definition enhances users' visual perception of the urban space. Bounding the spaces by at least one main street increases the accessibility to open spaces.
Safari	Green			
<b>Space Furnishing</b>				
Rehab		Red		Proper space Furniture reflects on users' perception of the space and forms a strong cognitive map. This creates a social relationship among users and enhances their sense of the urban space
Safari	Green	Red		
<b>Morphology of surrounding building</b>				
Rehab				Easier urban space morphology and functionality enhances users' perception of the space.
Safari				
<b>Pedestrian safety</b>				
Rehab	Red			Vertical separation positively effects forming identical cognitive map than the horizontal separation.
Safari	Red			
<b>Landmark</b>				
Rehab				Landmarks may have a positive or negative effect on forming users' cognitive image of the space.
Safari	Green			
<b>Paths</b>				
Rehab		Red		Path stresses users' cognitive map, particularly through walking activity.
Safari	Green	Red		
<b>Unobstructed view</b>				
Rehab				Unobstructed view enhances forming an effective cognitive map.
Safari	Green			

## **Part two (March 2017)**

The past ten years have witnessed wide spreading of open spaces food courts users. Hence, this part of the study is going to investigate the District food court which has been developed recently. The results of this part of the study apply the previously highlighted factors to deduct landscape change that has been developed over the past ten years and its effect on users' cognitive map.

### ***The District Sheraton***

The food court lies alongside the ring road between two main residential contexts. It mainly serves the resident of Heliopolis and Nasr city. The size of the food court is 180m\*120m. The food court is surrounded by Wadi Degla club from the north, the ring road from the east, the kids' area from the west, and the furniture Complex from the south as shown in Figure 2. The buildings surrounding the urban space have almost the same shape, finishing and colour. The space is mainly divided by one main path leading from the entrance and divided into two paths to embrace the lake which is considered the space landmark. The influence of and experience and age is perceived to be the maintenance and development of cognitive illustrations for surrounding environments.



Figure 2. Shows the layout of The District Sheraton

## **Results and Discussion**

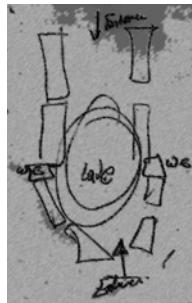
The results are divided into two sections

### ***Analysing cognitive maps***

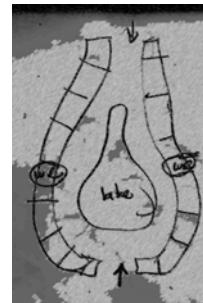
Through analysing the users' cognitive maps for the district open space as shown in figure 3, it has been found that most users' cognitive maps indicate mutual elements (Lake, Restaurant and café, toilets, Parking lots, and Stairs entrance) and also misses other mutual elements (Green areas, and Walking path). Hence, the researcher granted Singh's idea that discussed the relation between the age of the user and the precision of cognitive map which is well-thought-out as a directly proportional relation (Al-ghamdi & Al-Harigi, 2015).

Lynch (1960) indicated that paths and Landmarks serve as primary route-finding clues in urban spaces (Lynch, 1960). On the contrary, it has been found that the lake as the main landmark has drawn users' responsiveness, but only 33% of them have sketched the main path. Similarly, the researcher approved Downs and Stea idea (1973 & 1977) that stated missing any of the buildings in users' maps means that this building had not drawn the users' attention. Additionally, Gehl (2011) addressed the importance of drawing users' senses of

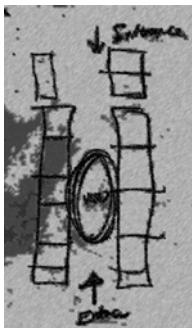
vision, hearing and smelling to develop an identical cognitive map (Gehl, 2011). Investigating the urban elements, the urban designer was able to attract the sight sense of the users, and this was noticeable in their maps, but he was not able to appeal the hearing and smelling senses of the users.



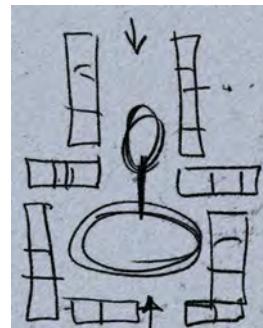
Male, age 18- 40, undergraduate student



Female, age 40 - 60, engineer



Female, age 18- 40, undergraduate student



Male, age over 60, police man

Figure 3. Users' cognitive maps

#### *Interviewing users*

The researcher has interviewed a number of users, as the questions aimed to show the users' desires and opinions. These questions are divided into three main sections. The first section aimed to detect the main function the users target the space for. The resulting percentages were indicated; 60 % eating, 20% reading, 10% walking and 10% watching shows. It is noted that users from age twenty to over fifty have grumbled about the far away distance of the children play area.

The second section mainly aimed to show the main activities that users implement in the space. These activities are; sitting, walking, and standing. Sitting at the space centre is chosen to be a preferable choice for users than sitting at the edges. Most of the users complained about the lack of the sitting places, and they showed their desire in preferring movable benches facing the view than fixed ones. Hence, siting uncomfortably affects negatively the users' cognitive map

The users agreed that the paving material of the path is really suitable for walking, except for the narrowness of the path that is not suitable for free walking. This caused manoeuvring or pushing or disturbance. Handicapped and mothers with baby stroller added that they do not prefer the presence of steps in the path. Which may be a clear cause for not illustrating the path in the users' cognitive maps as they are not able to perform free walking.

As for the standing activity, users have been distributed into two classes. Around 57% of them chose to stand under shelter, and 43% chose to stand in open space, but all the users chose to stand at space edge rather than standing at the centre.

The third section presents the results of the one to one interview with space users. Almost all the users have granted that urban space is utilised positively except for the remoteness of kids' area, and lack of places for sitting. As they can spend there from three to five hours inside the space, enjoying relief and containment. The space is vertically separated with lower steps, so users are rarely affected by the noise or the crowd of the surrounding streets. Through the researchers' daily observation, It has been found that eating, reading, and using laptops take place during breakfast time, walking activity during lunch time, and finally sitting activity during dinner time. Males preferred to spend their dinner time in the space, while females preferred to spend their breakfast and lunch time inside the space. Most of the users stated that the seasons affect the urban space's image. This can be observed in the changing image of the space during Christmas times and Ramadan. Nearly most of the users established that they got tangled among the morphology of the surrounding restaurants as the designs were almost alike. This fact explains Gestalt law (Jäkel et al., 2016) as the modest building are easily recalled and illustrated in users' maps, but also morphology repetition may lead to misperception.

## Conclusion

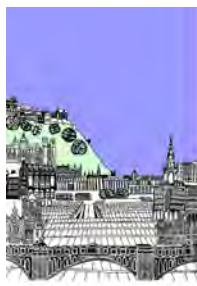
Very few studies attempt to evaluate open space design. Hence, this study attempts to fill this gap. It investigates the use of cognitive maps as a catalyst to develop open urban space design. Table 3 presents researchers' observation for the landscape change for the two parts of the study. A colour code has been used to signpost its effect on the ten previously defined criteria for the two parts of the study. The green colour indicates no change, while the red and green colour indicates a change process.

Urban Factors	Part one	Part two	Researchers' observations
Space size			Space size complied with theories recommendations
Space Enclosure			Space enclosure was better reflected in the later design, integrating both linear and circular space enclosure.
Entrances			Better accessibility is pronounced in the later design through providing two entrances
Space boundaries			Recommendations for space boundaries are achieved in the two parts of the study
Space Furnishing			No change furnishing was provided in the two parts of the study. Hence, recommendations of previous studies should be taken into considerations for providing space furnishing.
Morphology of surrounding building			Both parts followed Gestalt law, users feelings of redundancy and confusion are reflected in users' cognitive maps.
Pedestrian safety			The vertical separation promoted users' feeling of safety.
Landmark			Both parts followed Lynch's theory (1960).
Paths			Both parts show that case studies did not consider users' needs.
Unobstructed view			Both parts show compliance with the theoretical recommendations.

## References

- Adams, F. & Aizawa, K., 2010. *The Bounds of Cognition*,  
 Al-ghamdi, S.A. & Al-Harigi, F., 2015. Rethinking Image of the City in the Information Age. *Procedia Computer*

- Science*, 65, pp.734–743. Available at: <http://www.sciencedirect.com/science/article/pii/S1877050915028483> [Accessed February 27, 2016].
- Antrop, M., 1997. The concept of traditional landscapes as a base for landscape evaluation and planning. The example of Flanders Region. *Landscape and Urban Planning*, 38(1–2), pp.105–117.
- Atik, M., Isikli, R. & Ortaçesme, V., 2016. Clusters of landscape characters as a way of communication in characterisation : A study from side , Turkey. , 182, pp.385–396.
- Berto, R., 2005. Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology*, 25(3), pp.249–259.
- Brabyn, L., 1996. Landscape Classification Using GIS and National Digital Databases. *Landscape Research*, 21(3), pp.277–300.
- Brown, G. & Brabyn, L., 2012. An analysis of the relationships between multiple values and physical landscapes at a regional scale using public participation GIS and landscape character classification. *Landscape and Urban Planning*, 107(3), pp.317–331. Available at: <http://www.sciencedirect.com/science/article/pii/S0169204612001934> [Accessed March 22, 2016].
- Caspersen, O.H., 2009. Public participation in strengthening cultural heritage: The role of landscape character assessment in Denmark. *Geografisk Tidsskrift-Danish Journal of Geography*, 109(1), pp.33–45.
- Emmelin, L., 1996. Landscape Impact Analysis: a systematic approach to landscape impacts of policy. *Landscape Research*, 21(1), pp.13–35.
- Gehl, J., 2011. Life Between Buildings: Using Public Space. *The City Reader*, p.202.
- Hagerhall, C.M., 2000. Clustering predictors of landscape preference in the traditional Swedish cultural landscape: prospect-refuge, mystery, age and management. *Journal of Environmental Psychology*, 20(1), pp.83–90.
- Hoffmann-Kroll, R., Schäfer, D. & Seibel, S., 2003. Landscape indicators from ecological area sampling in Germany. *Agriculture, Ecosystems and Environment*, 98(1–3), pp.363–370.
- Huang, C.-J. et al., 2014. Application of cellular automata and type-2 fuzzy logic to dynamic vehicle path planning. *Applied Soft Computing*, 19, pp.333–342.
- Jäkel, F. et al., 2016. An overview of quantitative approaches in Gestalt perception. *Vision Research*, 126, pp.3–8. Available at: <http://www.sciencedirect.com/science/article/pii/S0042698916300475>.
- Jessel, B., 2006. Elements, characteristics and character - Information functions of landscapes in terms of indicators. *Ecological Indicators*, 6(1), pp.153–167.
- Lewandowsky, S. et al., 2012. Misinformation and Its Correction. *Psychological Science in the Public Interest*, 13, pp.106–131.
- Lynch, K., 1960. The Image of the Environment. In *The Image of the City*. pp. 1–13.
- Marcucci, D.J., 2000. Landscape history as a planning tool. *Landscape and Urban Planning*, 49(1–2), pp.67–81.
- Marwa Adel El Sayed, Ayman Mahmoud Hassan, I.E.B., 2015. *Land Suitability Analysis for Urban Green Areas Using New Methods and Techniques*, LAP LAMBERT Academic Publishing.
- Naveh, Z., 2000. What is holistic landscape ecology? A conceptual introduction. *Landscape and Urban Planning*, 50(1–3), pp.7–26.
- Nitavská, N., 2011. The method of landscape identity assessment. In *Annual 17th International Scientific Conference Proceedings, Research for Rural Development, Latvian University of Agriculture*.
- Palang, H., Alumäe, H. & Mander, Ü., 2000. Holistic aspects in landscape development: A scenario approach. *Landscape and Urban Planning*, 50(1–3), pp.85–94.
- Polat, A. & Akay, A., 2015. Urban Forestry & Urban Greening Relationships between the visual preferences of urban recreation area users and various landscape design elements. , 14, pp.573–582.
- Quinn, P.C. & Bhatt, R.S., 2012. *Encyclopedia of Human Behavior*, Elsevier. Available at: <http://www.sciencedirect.com/science/article/pii/B9780123750006001798> [Accessed January 22, 2016].
- Ruiz, J. & Domon, G., 2009. Analysis of landscape pattern change trajectories within areas of intensive agricultural use: Case study in a watershed of southern Quebec, Canada. *Landscape Ecology*, 24(3), pp.419–432.
- Swanson, C., 2002. Landscape Character Assessment. *Heritage*, p.90.
- Turner, S., 2006. Historic Landscape Characterisation: A landscape archaeology for research, management and planning. *Landscape Research*, 31(4), pp.385–398.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Indoor Environmental Quality Design for Advanced Occupant's Comfort – A Pre-post Occupancy Evaluation of a Green-Certified Office Building**

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**Abstract:** The aesthetic and functional appeal of high performance green-certified building is daunting. It creates a hyped expectation of better energy and indoor environmental quality (IEQ) performance that is usually hypothesized to improve occupant's health and productivity. Despite the favourability of this hypothesis, most recent studies have failed to prove these linkages leading to non-conclusive evidence of green building performance. Most previous limitations point to methodological deficiencies in quantifying occupant's experience, as well as the comprehensive measurements of physical and behavioural environmental factors of place in an integrated and comparative approach. The specific question of this project is whether a well-planned evaluation study with pre-post occupancy analysis of a retrofitted green-certified building could lead to more conclusive findings related to the impacts of green buildings, in general, and those with specific high IEQ on occupant's well-being, health, and productivity. This paper reports on a longitudinal assessment of a commercial high performance LEED™ double platinum retrofitted building. The building houses 800 employees working within 270,000 sq.ft. (18,000 sq.m.) of open-concept office space. The buildings were monitored for IEQ parameters of visual, thermal, acoustical, indoor air, and spatial comfort over a period of one year before occupancy and retrofit as well as a year after occupation. Continuous and intermittent measurements were performed and pre- /post-occupancy evaluation surveys were conducted. Results show strong correlations between improved visual, acoustical, and indoor air qualities of the retrofitted green environment that is well correlated with improved employee's productivity and satisfaction. Implications and spatial visualization are discussed as well as a continuous commissioning approach to improve the thermal environment through additional retrofits and occupant's behaviour. Proving that, for high performance buildings both the occupants and the buildings require on-going dialogue to ensure the occupants are able to adjust to the building systems and achieve its desired levels of performance.

**Keywords:** Post-Occupancy Evaluations, LEED™ Buildings, Indoor Environmental Quality, Field Studies. Multi-Comfort Assessment.

### **Introduction – The quest for high-performance buildings**

If you build it will they come? How would they feel when they occupy it? And in what ways does a high-performance office environment impact occupant's productivity, health and well-being? These questions summarize important, yet under studied, objectives of high performance and LEED™ certified green buildings. Not only do green buildings propose to combat the building industry's energy addiction, but they also promise the market a reduction in greenhouse gas emission, better indoor environmental quality, and more recently a value proposition that they provide better health and well-being for their occupants.

Employers, building owners, designers, developers, and investors throughout the world are persuaded, in response to an increasing marketing campaign by the building industry, that office design affects the health and wellbeing of occupants in many ways and so it is a smart business move to create green buildings that are healthy (Elzeyadi, 2016). With staff accounting for 90% of business operating costs, a 1% improvement in productivity can have a major impact on the bottom line and competitiveness of any business (Kats, 2003). Building developers, owners, and investors are also discovering the business value of delivering to their markets healthy and green buildings. In a survey of 200 Canadian building owners, for example, 38% of those who reported increased value said healthy buildings were worth at least 7% more than normal ones, 46% said they were easier to lease, and 28% said they commanded premium rents (WGBC, 2016).

Despite the favourability of this hypothesis, most recent studies have failed to prove these linkages leading to non-conclusive evidence of green building performance. Most previous limitations point to methodological deficiencies in quantifying occupant's experience as well as comprehensive measurements of physical and behavioural environmental factors in an integrated and comparative approach. The specific question of this paper is whether a well-planned evaluation study with pre-post occupancy analysis of a retrofitted green-certified building could lead to more conclusive findings related to the impacts of green buildings, in general, and those with specific high IEQ on occupant's well-being, health, and productivity. The paper builds on a previous interpretation framework of sustainable design as a place experience (Elzeyadi, 2015), thus acknowledging the complex systems of interactions between people and their indoor/outdoor environment on multiple layers relating to multi-comfort parameters, occupant's productivity, and symbolic perceptions of their building as a facilitator or inhibitor of performance.

### **Conceptualizing indoor environmental quality as a sustainable place experience**

Building on early definitions of place experience (Canter, 1991; Rapoport, 1989) this paper defined indoor environmental quality (IEQ) as all the qualities of the place that are collectively perceived and evaluated by its occupants as affecting their needs, wants, and the tasks they perform, without impacting the global environment in both products and process. Following a systems perspective, qualities of a sustainable place experience can be grouped in intellectual taxonomies according to their levels of meaning to occupants. These are: (1) sustainable attributes, which groups all the utilitarian qualities of the environment, (2) sustainable aesthetics, reflecting middle-level latent meanings, which represent value function qualities of the environment, and (3) sustainable ambience, higher-level symbolic meanings that are related to symbolic qualities of the environment (Elzeyadi, in press). Each level of meaning will group a number of qualities that form a profile. Each of these qualities can be perceived as a "negative" or "positive" attribute of the environment depending on whether it facilitates or inhibits the occupants' experience, as well as how well it satisfies their wants and needs. The paper adopts a systems interactions framework between occupants (people), their settings (buildings), and place (environment) following the triple bottom-line approach epistemology that defines sustainable place experience.

### **The Study Context – A double Platinum LEED™ Office Building**

To validate the proposed IEQ model, different spatial configurations and IEQ design strategies were assessed and measured for a double platinum-rated LEED™ building (USGBC LEED v3 Core and Shell and Commercial Interiors) over an extensive 18 months renovation. The

existing building was stripped down to the steel and concrete structure and enclosed with a high performance building envelope and glass façade. The interior open-plan office space was designed to maximize occupant comfort, as well as improve the health and well-being of the employees. The four-story 25,734 sq.m. headquarters is located on a 263,046 sq.m. mature landscaped site, 40 kilometres west of Philadelphia in Malvern, Pennsylvania, USA. The corporate site includes 18,000 sq.m. of open-plan office area, 116 collaborative spaces, a cafeteria, pantry areas, a fitness centre, a pond, outdoor workspaces by a rainwater fountain and 2.1 km of walking trails to further enhance the employee experience (Figure 1).

The state-of-the-art facility was designed to promote cross-collaboration, as well as attract and retain talent. Sweeping views of nature that provide an abundance of natural light are possible from 92% of the interior space. Continuous fresh air ventilation and no- or low emitting materials were employed to create excellent indoor air quality. Acoustic comfort at the 800 plus workstations was created through the thoughtful placement of sound absorbing surfaces, noise reducing interior partitions and an active sound masking system.



Figure 1: The building complex before (right) and after retrofit (left)

### **Indoor Environmental Quality and Multi-Comfort Analysis – Multi-method Approach**

Multi-Comfort parameters and metrics with the thermal, visual, acoustical, and air quality environment were assessed and analysed for both before and after green retrofitting the building. Both instantaneous and long-term field measurements data of the physical

environment and multi-comfort parameters were collected at the level of the building as well as the scale of the occupant work setting. Environmental sensors and data loggers measuring temperature, relative humidity, air velocity, and air movement stratified across the different floor levels of the buildings, were deployed over the winter, spring, and summer seasons respectively. In addition, infra-red (IR) and high dynamic range images (HDRI) were taken over the course of sampled seasonal days for the occupants workstations and from their direct view sheds employing wide angle and fish-eye lenses to simulate their perspective and field of vision. The different imaging techniques were employed to document surface temperature, mean radiant temperature, and glare indices over the study period. In addition, acoustical attenuation, sound levels, and speech intelligibility measurements were recorded for typical office simulated conditions in the field at different times before and after the retrofit. To evaluate indoor air quality, approximately 15 litres of air was sampled for high performance liquid chromatography (HPLC) and mass spectrometry analyses as well as volatile organic compounds (VOCs) concentrations (see Figure 2). Airborne particulate concentrations were measured using a light-scattering laser photometer in the near-infrared light range.

Occupant's perspective and satisfaction was collected by employing a series of structured and open-ended focus groups. Each focus group included 10-15 employees representing different job-levels and workstation locations. This was followed on by administering an occupant survey to the entire employee population before and one-year after the move into the green-retrofitted office building. Response to the survey was very high with 289 employees completing the questionnaire before the move and 320 completing it following the move. Data tabulation and coding were performed on both the physical and human-response data sets. Physical measurements and survey responses were spatially tagged and statistically analysed using SPSS software. In addition, data visualizations and multi-comfort parameters were computed using a suite of software that spatially analysed the occupant's visual, thermal, acoustical and indoor air quality (IAQ) across various locations of the building.

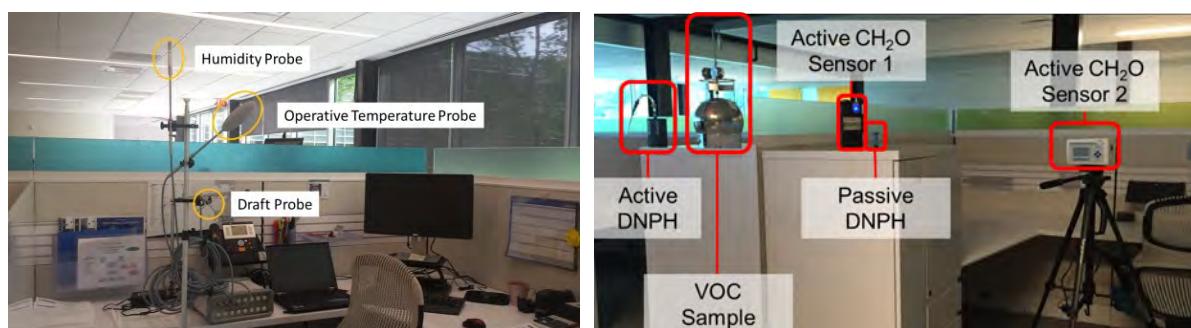


Figure 2: Research Methods and Instruments Used

### **Visual Comfort Analysis**

To evaluate visual comfort inside multiple LEED™ certified work environments, we measured lighting distribution metrics; useful daylight autonomy (uDA100-1000), visual asymmetry, and glare in the field of vision using five glare analysis metrics (DGP, DGI, UGR, VCP & CGI). A comparative analysis reveals how different spatial configurations and proportions between the two phases of the buildings impact both daylight level distribution and glare. With improved envelope performance (Tvis & SHGC) of the glazing as well as higher light reflectance values of space finishes, the green retrofitted building shows more than 70% improvement in daylight distribution. Furniture layout and the provision of flexible working

spaces around the perimeter without cubicles and partitions show substantial impacts on daylighting performance and glare management of the green retrofitted space. This green-retrofit provided better daylighting distribution ( $uDA = 74\%$  and  $DGP = 10\%$ ) over the pre-retrofit condition ( $uDA = 27\%$  and  $DGP = 40\%$ ) in this sampled location (Figure 3).

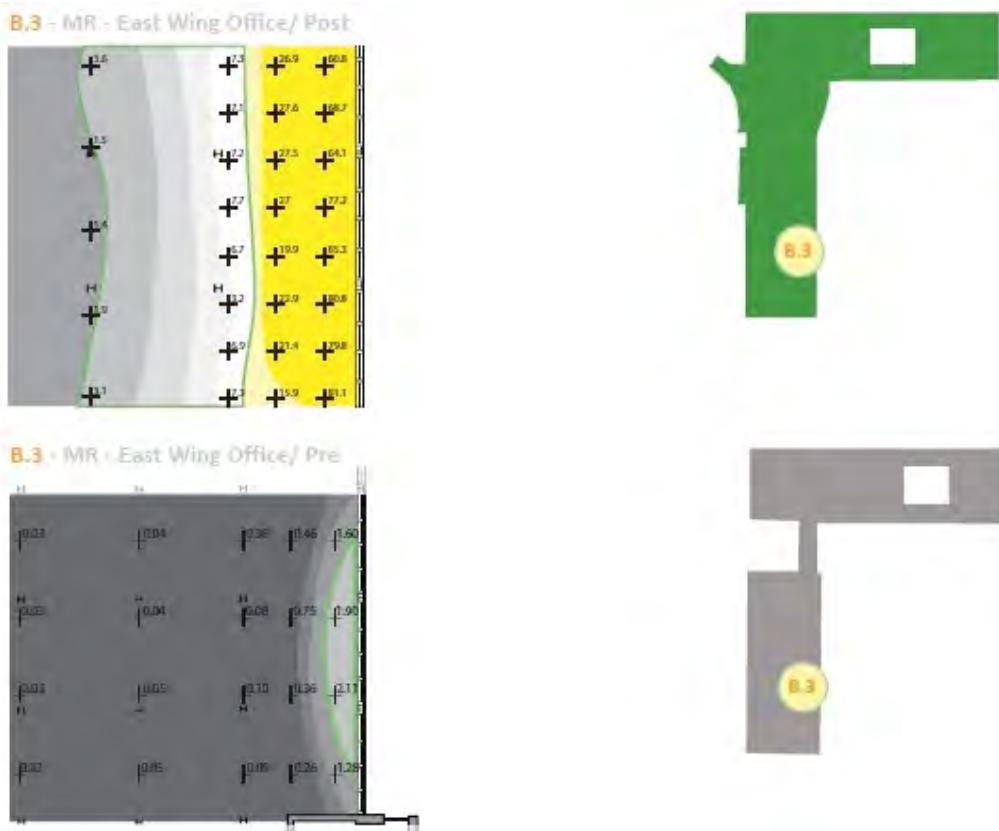


Figure 3: Comparative Analysis of Visual Comfort Metrics for a Typical Floor Area of the building (after retrofit, top and before retrofit, bottom)

### ***Thermal Comfort Analysis***

Thermal comfort metrics were calculated using the measured data and equations described in ANSI/ASHRAE Standard 55-2013. Thermal comfort is visualized for sampled locations using the a Thermal Comfort Plot on the psychrometric chart for both the pre- and post-green building retrofit conditions while acknowledging the occupant's presumed metabolic rate (met) and clothing level (clo).

Figure 4 provides a comparative plot of occupied hours for a typical workstation in the spring season for both phases of the building. Each dot in the psychrometric chart represents the thermal conditions for one occupied hour during a typical spring work day. Pre-retrofit, thermal conditions ranged from completely outside the comfort zone for perimeter workstations (orange dots) to partially within the comfort zones or in-between the comfort and adaptive zone for internal work zones. In contrast, most of the thermal conditions after retrofit fit nicely within the thermal comfort area yet provide enough variation to avoid falling in thermal boredom conditions and still reflect diversity in thermal conditions suitable for occupants' different clothing and metabolic levels within the space in different times of the day.



Figure 4: Comparative Analysis of Thermal Comfort Psychrometric Charts during Spring Season of both Building Phases (green post-move/retrofit, red pre-retrofit, orange pre-move and black outdoor)

### ***Indoor Air Quality***

Formaldehyde concentration was evaluated in conformance with EPA Method TO-11 (US EPA 1999). Approximately 15 litres of air was sampled using collection pumps with flow rates operating at 0.125 l/min. The samples were transported to an accredited laboratory for extraction and analysis using high performance liquid chromatography (HPLC). Air testing for volatile organic compounds (VOCs) was conducted by EPA Method TO-15. The procedure includes analysis by HPLC combined with mass spectrometry. Results of the indoor air quality evaluation are graphically displayed in Figure 5. Values were normalized to exposure limits for each parameter and scaled to 100 percent. Indoor environmental conditions for comfort and gas concentrations were all well below exposure limits for each category.

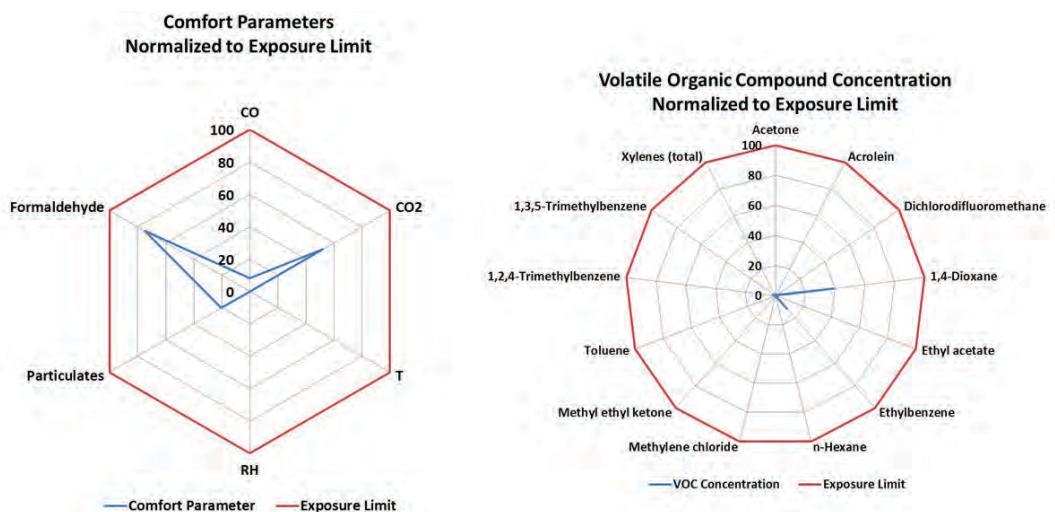
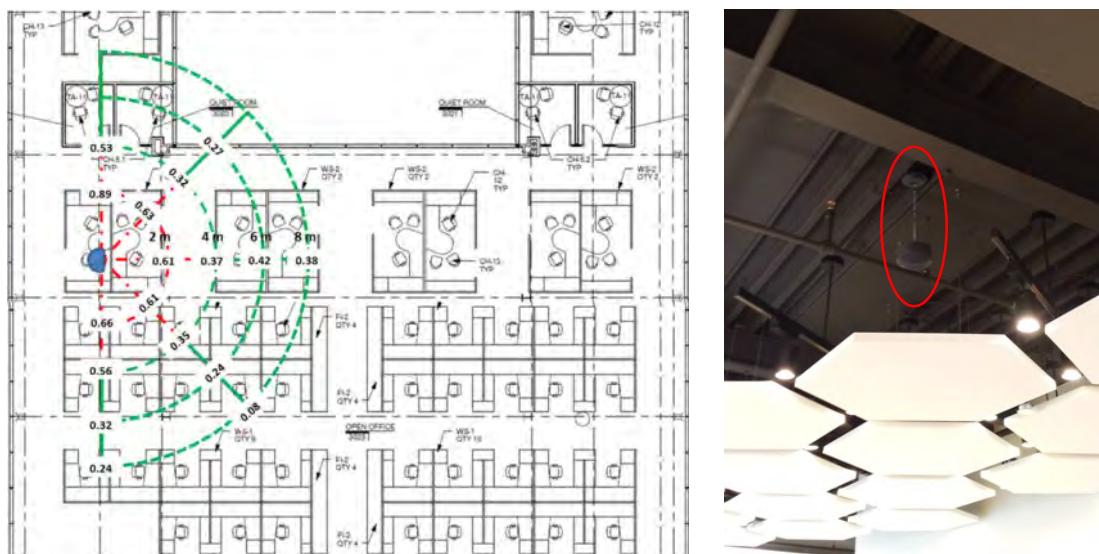


Figure 5: Comfort Parameters and Gas Concentrations Normalized to Exposure Limits

### **Acoustic Comfort Analysis**

The challenge of acoustic design in open concept office spaces is to limit sound reflections and noise levels in large spaces, while creating acoustical privacy at individual workstations. Acoustic comfort can be achieved through the use of sound absorbing surfaces, high performance noise reducing interior partitions and exterior facades, as well as sound masking systems. Managing speech intelligibility between workstations is the goal, so that employees are not distracted by their office conversations. Sound masking systems were employed to generate white noise in the space. The recommended noise criteria (NC) curve limit for open plan office spaces with forced air distribution systems is NC-40 or less. Several workstations were evaluated for spatial sound distribution of the speech transmission index to assess the distraction distance from the speaker where the speech transmission index falls below 0.50. Acoustic comfort mapping for spatial decay and distraction distance with STI is illustrated in Figure 6. Results highlighted by the green lines indicate that the desired distraction distance is achieved within 2 to 4 meters for most locations.



### **Indoor Environmental Quality - Occupants Perspective Analysis**

In addition to physical assessments and visualization of the multi-comfort metrics of the environment, an occupant questionnaire was administered to solicit employees' satisfaction of both buildings. Questions were added to address specific issues such as Thermal and Visual comfort of the various spaces. An average of 32% of the employees for pre-retrofit in and 32% of the employees for post-retrofit completed the questionnaire. Preliminary results of the survey show strong occupants satisfaction with the environmental agenda and green/LEED™ certification of the building. More than 75% of occupants in the retrofitted building agree about the importance to work in a building that is environmentally conscious (Figure 7).

### **Conclusions**

The main objective of this paper is to provide detailed as well as context specific information to assess IEQ inside green buildings from a comprehensive approach. By establishing a comparative approach between a traditional building pre-retrofit and its green retrofitted LEED™ certified platinum phase, the study provides an evidence-based guide of green

building design strategies that impact IEQ parameters. It is important to note that green strategies should not be perceived as “one size fits all” in general and might not be suitable in all design situations. Designers will need to balance pros and cons of green systems as they manage the value proposition of the impact of green buildings on IEQ and occupant’s comfort with actual performance of spaces and the design of a quality environment. This paper provides an overview of a comprehensive study that will be reported-on further with more details in future publications and analyses. The hope is to spur future research to apply the proposed model and contribute to a better understanding of the nature of IEQ in buildings beyond our over fascination of their promised performance and marketing hype. Results show strong correlations between improved visual, acoustical, and indoor air qualities of the retrofitted green environment that is well correlated with improved employee’s productivity and satisfaction. Proving that, for high performance buildings both the occupants and the buildings require an on-going dialogue to ensure the occupants are able to manage the building to achieve its desired levels of performance.

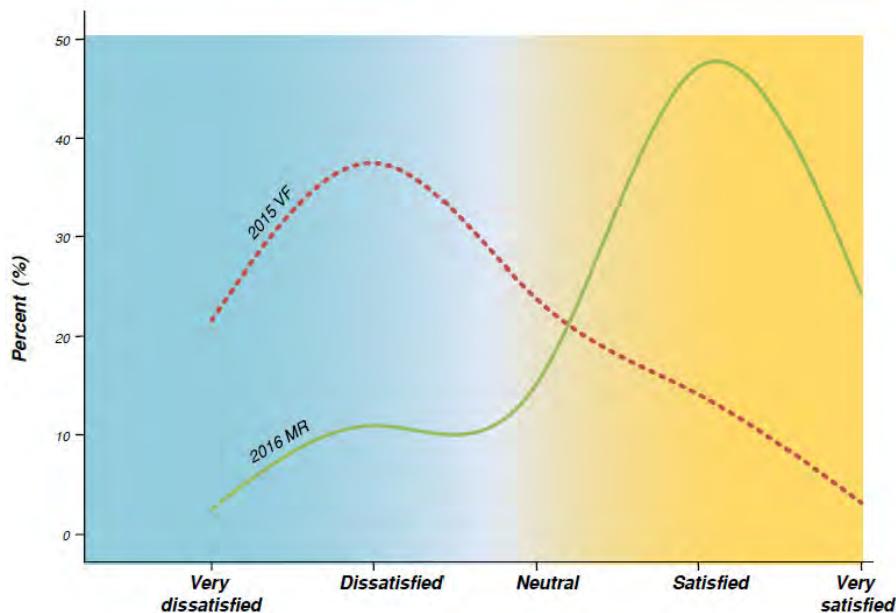


Figure 7: Occupant's Satisfaction Percentages from a POE Building Survey of Both Studied Building Phases

## References

- Canter, D. (1991). Understanding, Assessing, and Acting in Places: Is an integrative Framework Possible? In T. Garling and G. Evans (eds.) *Environment Cognition and Action*. New York: Oxford University Press.
- Elzeyadi, I. (in press). A Comparative Analysis of Predictive and Actual Performance of High Performance LEED Buildings. In W. Prieser, U. Schramm & A. Hardy (eds.), *Building Performance Evaluation: From Delivery Process to Life Cycle Phases (Second Edition)*. NY: Springer.
- Elzeyadi, I. (2007). Healthy Offices: Windows, Absenteeism, and Health in Work Environments - Evidence Based Guidelines. World Congress on Design & Health (WCDH 2007), June 29 to July 1, 2007, Glasgow, UK.
- Elzeyadi, I. (2003). Environmental Quality - Shaping Places for People: A Systemic Framework for Conceptualizing People and their Workplaces. In: *Shaping Places for People*, pp. 71- 79. Proceedings of the Environmental Design Research Association EDRA 34th Conference. May 22-26, Minneapolis, Minnesota.
- Kats, G. et al. (2003). The Costs and Financial Benefits of Green Buildings: A Report to California's Sustainability Task Force. October 2003. Available at [www.cap-e.com](http://www.cap-e.com).
- Rapoport, A. (1989a). Environmental Quality and Environmental Quality Profiles. In N. Wilkinson (Ed.), *Quality in the Built Environment*. New Castle (UK): Urban International Press.
- World Green Buildings Council (WGBC) (2016). *Building the Business Case: Health, Wellbeing and Productivity in Green Offices Report*. Toronto, Canada: Eva Phoenix.



# PLEA 2017 EDINBURGH

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## Active House Label – tool to empower house owners and developers to design sustainable buildings

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**Abstract:** Active House is a vision of buildings that combines energy efficiency with specific attention to users health and comfort. It include design guidelines, specifications and evaluation tools, and focus on parameters that has relevance and direct influence on the qualities for the homeowner. In order to empower house-owners, architects and professional house builders to design sustainable buildings; the Active House alliance has developed a label, that can be given to projects that meet the Active House requirement and focus on combining requirement to building design with people's concerns regarding comfort, health, energy, safety and environment. It is the holistic view on buildings and the combination of quantitative and qualitative parameters that makes the Active House label unique and it is the focus on affordability and human aspects that makes it valuable for homeowners. A building being labeled must be calculated and evaluated on 9 parameters within comfort, energy efficiency and environment and the calculation must be validated by an independent body.

**Keywords:** Sustainable buildings, Active House, Indoor comfort, Energy efficiency, Label

### Active House

Active House is a vision of buildings that combines energy efficiency with specific attention to user health and comfort, indoor climate and the environment. Active House focus on Comfort, Energy and Environment, and require a holistic view.

An Active House is evaluated on the combination and integration of the three main principles of Comfort, Energy and Environment. The evaluation has to be done in accordance with the Active House specifications and the performance are described through the Active House Radar (Fig 1) showing the level of ambition of each of the three main Active House principles and their nine sub-parameters.

The integration of each parameter describes the level of ambition of the building. For a building to be considered as an Active House, the level of ambition can be quantified into four levels, with 1 as the highest and 4 the lowest.

The building must be evaluated and benchmarked on the nine sub parameters, (Daylight, Thermal Comfort, Air quality, Energy demand, Energy supply, Primary Energy, Environmental load, Freshwater, Sustainability) where each of them is evaluated in accordance with international standards, like EN15251, ISO14040 as well as national standards and methodologies for i.e. energy demand. Some of the parameters are included in building legislation and in this sense, the methodology used on national level can be reference.



Figure 1. Active House Radar



Figure 2. Active House Label

### Active House Label

The Active House label (Fig 2) is a quality stamp for comfortable and sustainable buildings. It is based on elements that are important to humans life and living in their homes. It can be given to projects that have been evaluated in accordance with the Active House specification and has been verified by an independent body.

The label is a sign to homeowners that this building is designed with focus on human needs and a home fit for the future. In order to obtain the Active House label, a project must be benchmarked on the nine sub parameters mentioned above. As some of the parameters are topics that are not yet a legislative requirement to buildings, the label can only be given to buildings that exceed the legislative requirement and focus on more qualities to buildings, like health, comfort and environment.

The evaluation of a project must be carried out by use of the Active House calculation methodology and can be carried out by the architect or a consultant. The calculation is verified by an independent body approved by the Active House Alliance. The independent body carry out a screening of the project and make a sample evaluation on two or more parameters in order to verify the calculation. Based on the outcome of the verification a project can be given the label.

The Active House label was introduced during 2016 and the first five projects has already been labelled. The following projects has been labeled in 2016 and show some of the qualities by an Active House approach to building design.

### Active House Centennial Park – use passive solutions to create good indoor comfort

Great Gulf's Centennial Park Residence is the first labelled Active House. The Active House evaluation (Fig 3) shows how the comfort parameters has been a main focus area, with high score on air quality, thermal comfort and daylight. The home is designed to improve human comfort and well-being. The design is the result of highly process-driven approach to building an energy-efficient home with the use of the Active House vision as guidance. It is developed through the collaborative expertise of a team of Building Science professionals, award-winning architects and Great Gulf, a Canadian home builder committed to evolving the Active House concept in Canada.



Figure 3. Centennial Park Radar



Picture 1: Active House Centennial park

The project includes a clean modernist architectural aesthetic design with energy-saving and environmentally conscious features such as interior and exterior LED lighting systems, low-flow water fixtures and finishes that are easy to maintain. But what ultimately makes this home so appealing is an approach to design that maximizes opportunities for natural daylight and natural ventilation.



Picture 2: Well daylit ground floor due to windows with different orientation and C shaped courtyard

The quality of the design is shown by the strategic use of natural daylighting that defines the true character of the Great Gulf Active House where little to no artificial lighting is required during the day. Visitors immediately notice the light-filled double-height C-shaped courtyard which forms an architectural “anchor” for the entire home. The ground-floor is laid out in an open plan with no barriers to obstruct daylight. And double-height spaces vertically connect upstairs spaces.

To reduce the energy required for air conditioning, Active House Centennial Park contains features that boost air quality while reducing energy for ventilation. Large operable windows and roof windows facilitate natural ventilation and ventilative cooling to keep the house cool during warmer months while ensuring effective ventilation throughout the year. Fully programmable windows feature an intuitively designed intelligent interface to maintain their automatic functioning for natural ventilation purposes.



Picture 3: Double high rooms create good daylight and is optimal for natural ventilation

### **RenovActive – comfortable and affordable renovation for replication**

Renovactive is the first renovation project that has received the Active House label. It is designed with focus on affordability , replication, as well as healthy and comfortable indoor comfort. These were the main criteria set up for the RenovActive project, a single family house of the social housing company Foyer Anderlechtois, located in Anderlecht, Belgium. The aim of the renovation project was to test the Active House principles in social housing and single-family homes.



Figure 4. RenovActive Radar



Picture4. New attic and facade *insulation k*

The project aim to become a guide for how to renovate houses with focus on excellent indoor climate with a good energy performance, therefor several renovation scenarios were considered and their performance was analysed according to the Active House specifications.

The final project is an example of affordable and replicable renovation techniques that not only improves the energy efficiency of the dwelling but perhaps more importantly, focuses on providing the best possible indoor environment (fig 4).

The design targets for indoor climate, energy and environmental impact are based on the Active House Specification. As there is a clear financial frame for the house, the approach in the design process was to evaluate different scenarios that combined different technical solutions. Each scenario was evaluated according to the Active House radar diagram (fig 5).

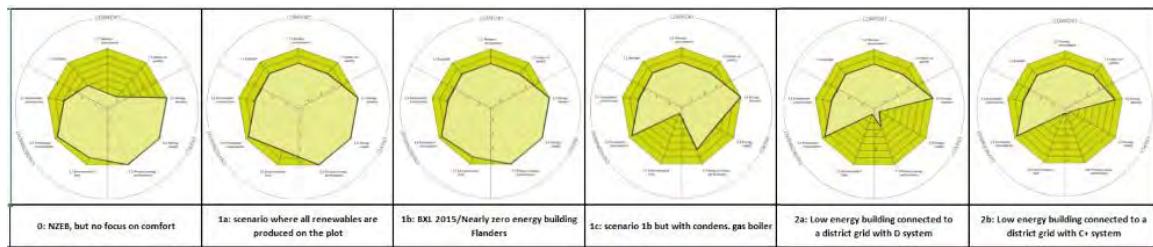
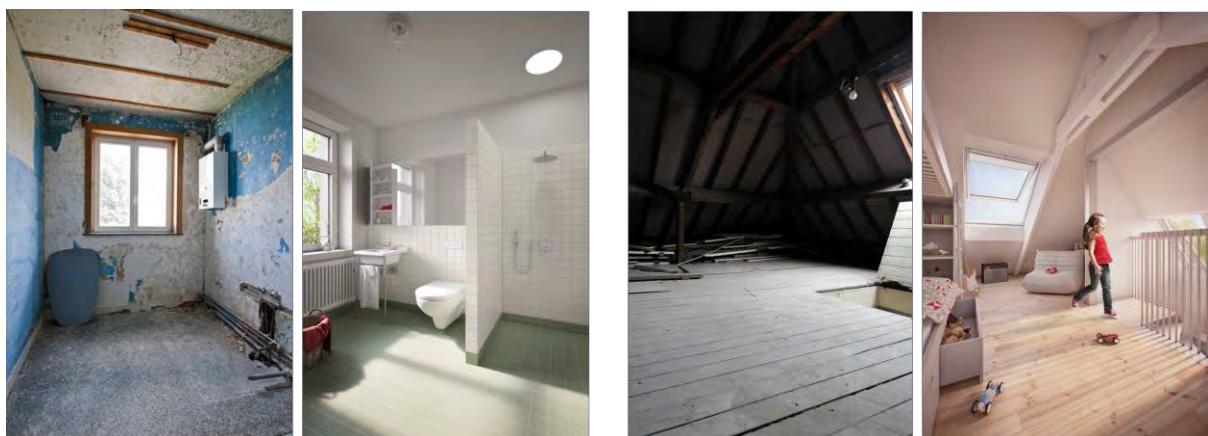


Figure 5 Six out of nine different scenarios based on Active House

The RenovActive House includes a number of replicable elements that constitute the RenovActive concept. All of the elements are implemented as separate units of products and solutions, and optimise essential home performance parameters in relation to energy, comfort and indoor environment – the three pillars of the Active House concept. This flexibility and inherent scalability makes it possible to replicate the project to other buildings in the neighbourhood and match their respective budget.



Picture 5: Before and after renovation of the bathroom and the attic

The RenovActive project focuses on providing maximum daylight. A Daylight Visualizer was used to simulate daylight levels in the building, revealing excellent levels of natural light after renovation. The new roof windows in the new attic will be a good source of natural light and give the inhabitants indoor comfort all year round.

In view of the glazed surfaces, which guarantee levels of natural light and passive solar gains in winter, it is important to control excess heat using fully automated solar protection. The opening and closing of the exterior blinds will depend on the hours of sunshine and the outdoor temperature. The windows will also be fitted with interior blinds that will control the light as desired.

To ensure a healthy indoor atmosphere and a maximum of fresh air in the house, a natural ventilation system is fitted. When the outside temperature is over 14°C, an automatic window-opening system will be used. Natural ventilation will be controlled via intelligent window systems, which makes it possible to easily open or close windows. Sensors (humidity, temperature, CO<sub>2</sub> etc.) integrated into the ventilation unit control the opening of the windows, guaranteeing excellent indoor air quality. In winter, air is let in by ventilation flaps integrated into the windows. This ensures maximum air quality and comfort: the ventilation levels adapt to user needs in real time. This system also saves energy, as it avoids excessive ventilation.

A proposal was made to place solar panels on the roof of the garden shed to heat water but the additional cost generated by the solar collector does not meet the social housing budget for a project like RenovActive and therefore the amount of renewable energy installed on the building is low. However the main issue was to reduce the energy demand and this has been reached by reduction to 60 kWh/m<sup>2</sup> for all the energy need in the building, including heating, domestic hot water, ventilation, technique and lighting. In order to reduce use of water, rainwater will be collected in a 5,000 litre tank and reused for flushing toilets, the washing machine, use in the garden, etc.

### Green Solution House

Green Solution House is the first labelled conference and hotel centre, and it is the winner of the Active House Award 2016. The main target with the project is to inspire visitors by offering a comfortable stay in a healthy and creative environment. The building and landscape show a holistic approach to sustainable design, emphasising regenerative solutions including healthy indoor climate, renewable energy sources, active materials and recyclability. The design of the building itself is based on several parameters to show a holistic approach to sustainability. The building is based on the criteria of the Active House vision (fig 6).



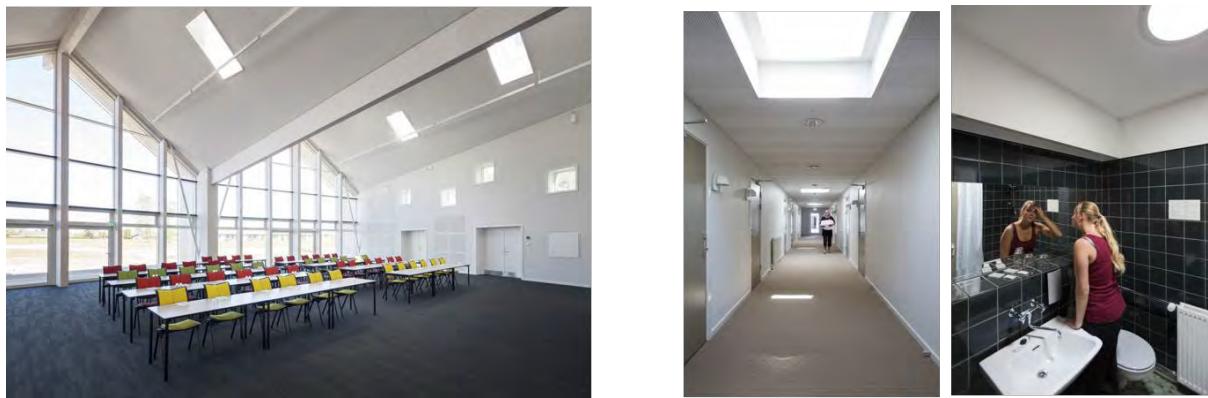
Figure 6. Green Solution House Radar



Picture 6 Garden view - Green solution House

The cycle of natural light is fundamental to humans wellbeing and ability to maintain a healthy circadian rhythm, as well as daylight improves humans productivity and ability to focus.

Therefore the conference rooms at Green Solution House are designed to accommodate meetings in broad daylight, utilizing diffused light from the north. Inside the hotel rooms, daylight conditions have also been optimised with retrofitted glass balconies. Sun Tunnels and light cables redirect daylight to every nook and corner, where natural light is limited, like in bathrooms. In all common areas and hallways, skylights are utilised to create a comfortable indoor climate with generous daylight levels. Altogether, a strong focus on daylight driven design has helped to create well-lit spaces, resulting in better user experience and less energy consumption.



Picture 7: Daylight conditions - optimized in dark rooms like conference rooms, hallways and bathrooms

Clean air is essential to optimising the quality of indoor environments. Green Solution House have created a variety of solutions that contribute to keeping the air fresh and pollutant free. The carpets on the floor absorb dust particles, the plasterboard on the walls take care of formaldehyde, and the roof membrane captures and neutralises pollution particles from traffic. The Green Wall in the Third Climate Zone naturally purifies the air with plants and balances humidity levels.



Picture 8: Supply of clean air is created by use of green wall, permeable ceilings and natural ventilation

The architect has focused on balancing the thermal environment for optimal indoor comfort, by balancing natural ventilation, mechanical ventilation with a heating strategy that response to the seasons. This strategy has resulted in the highest score possible in the Active House analysis of comfort in the building (fig 6). The diffuse ventilation strategy supplies fresh air through permeable acoustic panels in the conference center and restaurant ceiling and has two major advantages in terms of indoor climate. First, the even distribution cools the air without causing discomfort and drafts, and thus reduces supply air requirements and duct sizing.

### **Looking forward**

The three cases shown before have all been developed on the basis of a sustainable guideline that include a higher focus on sustainability than just energy savings. It is shown that by use of such tools the building design is balanced between indoor comfort issues and energy efficiency. All the buildings have been designed with an Active House philosophy in focus.

It is already proven that environmental schemes like BREAM, LEED, DGNB has moved the focus from purely focus on energy use to a more holistic view on sustainability, which include parameters like indoor climate, sustainability, sourcing and energy efficiency.

However many existing programs for environmental benchmarks of buildings are developed for larger scale buildings and have – due to complexity and costs - limited relevance for single family homes and small buildings. By implementation of a simple systems which cover the main sustainable parameters, like Active House and other similar systems, the awareness and utilization of sustainability for small and medium size buildings grow.

The existing labelling of small buildings are based on the compulsory energy labelling schemes and similar schemes that focus on energy efficiency and heating demand. Those schemes do very seldom cover other parameters like sustainability, daylight and indoor comfort. Thereby the focus on human needs in the building have a risk of becoming a second priority.

By use of the Active House principles and its nine parameters there are now a simple scheme available for single family homes and smaller buildings, that can drive the development of a more holistic view on sustainability in this segment

## References

- Active House Alliance. (2013). *Active House specification*. 2 edition.
- Rode, C. Eriksen, K. (2013) Active House Specification - evaluation of comfort, energy and environment in buildings. *REHVA Journal* (03.2013)
- Richard Lyall, (2017) 4 Things that make Active House stand out. *The Toronto Sun* (3.2.2017) New home and Condos p 9
- Marcus Mitanis (2016) Great Gulf Celebrates World's First Certified Active House  
*Urban Toronto.ca* (13.6.2016)
- Jeremy\_Williams (2017) Building of the week: RenovActive. *makewealthhistory.org* (24.3.2017)
- Alison Furuto (2012) Green Solution House / 3XN. *ArchDaily* (19.1.2012)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Soft Landings Driven Design Management process: Achieving sustainability in a school building in the UK

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**Summary:** One of the challenges facing the industry is closing the energy performance gap in non-residential buildings. Despite various recommendations and introduction of new technology, the problem remains widespread. Debate on how designers and architects can contribute to finding solutions to this problem continues. Soft Landings has been on the forefront of encouraging the delivery of buildings where estimated energy targets align with actual targets. This paper investigates the working processes of a Soft Landings design team; using Interviews, walk-throughs and contract documentation of the project. The paper explores the design management side in a Soft Landings process. How end users and sub-contractors were involved during the design stage of the project and how decisions taken affected the outcome of the project. The study discovers that learning from past projects plays an important role for new projects in achieving their goals with respect to energy efficiency and sustainability. Participation of the end users need to be coordinated to maximise their advantage without sacrificing time and cost. Additionally, practical implications are presented for architects about the involvement of end users in a Soft Landings project.

**Keywords:** Soft Landings, Design Management, Energy performance gap, Sustainability, Non-residential buildings

### Introduction

The link between energy performance of buildings and its design has been established (Bordass and Leaman, 2005). Proving that complex and complicated designs often make it difficult for building managers to correctly operate Building Management Systems. This affects the energy performance of buildings with the estimated energy usage higher than actual usage. This difference is known as a ‘performance gap’ (Gupta and Gregg, 2016) and negatively affects building owners and end users. This is most prevalent in non-residential buildings (Axon et al, 2012) and leads to missing energy, sustainability, and overall carbon emission targets (Fedoruk et al, 2015). The concept of sustainability in design and construction covers a wide spectrum of interconnected elements (Burnett, 2007). From Burnett’s definition, of the 3 scopes of sustainability (social, environmental, and economic), this paper looks at sustainability from the environmental definition which means that building targets go beyond CO<sup>2</sup> reduction to consider the building lifecycle.

In 2004, the aspiration for schools to be ‘models of sustainable development’ was a result of the 1997-2010 labour government policy (Moncaster and Simmons, 2015). This brought sustainability to the forefront of school building projects. The government called on construction companies to act to make school buildings more sustainable and required individual designs to achieve a ‘Very Good’ rating in BREEAM assessment tool. In response

to this, construction companies intensified their focus on environmental sustainability targets in schools (Moncaster and Simmons, 2015). A report by the government (DfES, 2006) outlined six themes for sustainable schools. They were ‘stakeholder engagement’, ‘getting the basics right’, ‘low energy design’, ‘renewable energy systems’, ‘managing energy and ICT’ and ‘the building as a learning tool’. The fact that stakeholder engagement was the first on the list underscores the importance of the design team’s relationship with the client and end-users.

Soft Landings aims to achieve project targets of energy efficiency and environmental sustainability by closing the performance gap (Way and Bordass, 2005; SLF<sup>1</sup>, 2014). It calls for greater collaboration between all stakeholders of a project from the inception to handover, aftercare and extended aftercare. Until recently, designers did not consider how the end user was going to operate a building (SLF, 2014). The introduction of complex building systems (heating, cooling, ventilation, lighting) has presented an opportunity for the design team to involve not only the construction team but building managers and end users. This collaboration, therefore, will be in the form of high-level multi-layered information exchange (SLCP<sup>2</sup>, 2014; Gana et al, 2017). This will involve regular reality checks and feedback throughout the project. Usually by a Soft Landings Champion who is a member of the team but has the extra role of ensuring the realisation of project targets.

This paper looks at a primary school in London which used Soft Landings at various stages during the construction of an extension block. The main research question is ‘how were the principles of Soft Landings applied to the project during the design stage?’ The paper will provide a working insight into the design process of a Soft Landings project. Using interviews with the design team, it will look specifically at the interactions between the design team and the end users and how feedback was collected and incorporated into the design. The paper will also discover how the use of information from an earlier school project helped to inform the design and the lessons learnt in the process.

## **Methodology**

### ***Case Study***

The method for investigation in this research was case study. This allowed the investigation of the complex interaction between the design team, end users and other professionals within the natural setting of the ‘case’ (Yin, 2003). Case study also allowed the research to get a multidimensional insight into the Soft Landings design process and probe deeper into specific situations. This paper investigated a single school project to discover the interaction of the design team with end users and other professionals during the design stage. According to Flyvbjerg (2006), generation of theory from a single case is possible depending on the selection process of the case. Leaman, Stevenson and Bordass (2010) agree; stating that a single case can shed light on new issues and processes and create hypothesis that can be tested. The study was carried out after completion to give the occupants a chance to experience the building and find out any issues discovered during the post occupancy evaluations. The focus of the case study, however, was the design stage of the project. The building is a school in the south-west of London procured via a framework agreement

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<sup>1</sup> SLF: Soft Landings Framework; this literature was originally developed by BSRIA in 2008

<sup>2</sup> SLCP: Soft Landings Core Principles; this literature was developed by BSRIA and the Soft Landings User Group

with the local council, the main contractor and property consultants. The client held a mini competition with the winning design team engaged by the main contractor. The brief called for an extension of a classroom block consisting of 8 new classrooms, a library and ICT suite, deputy head's office, and a separate kitchen and dining room. The contract was awarded in 2010 with the contract sum of £2,530,000 and obtained a BREEAM 'excellent' rating for design.

### **Data Collection and Analysis**

The researcher carried out a walk through the designed spaces to see how the occupants interacted in the building. Notes on the public consultation and the 'visioning workshop' were also used to find out how the user feedback was collated. Data was collected using semi-structured interview with the project Architect, Project Manager, and the M&E subcontractor (Mechanical Engineer). The questions were open-ended to allow each respondent to give their own unique view of the project. The questions were based on the literature review which highlighted certain factors as barriers to achieving sustainability; and a report on the post occupancy evaluation of the building from the building data exchange (BDE, 2014). Specific questions were designed around these factors to allow investigations. The questions were divided into 2 sections with the first section establishing profession, level of experience and level of knowledge in Soft Landings. The second set of questions were about the design process with respect to Soft Landings and end user participation.

Each professional was interviewed for about 1 hour. The ethics review board from the University of Kent approved the interview questions and format. Information on the research and consent forms were distributed prior to the interviews. The information was anonymised as stated on the information forms. The interviews were transcribed and copies sent back to the respondents for approval before analysis. Nvivo software was used to store the information and generate codes. A combination of descriptive and analytic codes were generated. The emerging themes were compared to those from the literature review to develop the final codes.

### **Findings and Discussion**

The interview revealed how the design team interacted with the end users and other professionals to achieve the project sustainability goals. These are discussed under the themes generated by coding.

#### ***Soft Landings at the design stage***

The client wanted this project to showcase its new sustainability policy, as such the brief reflected its demands.

**Interviewer:** '*how were the project objectives included in the design?*'

**Architect:** '*We worked within the brief and wanted sustainability to be a core objective of the project. I suppose the client was quite keen on promoting sustainable and energy efficient buildings.*'

**Project Manager:** '*the objective of the project was to have the new buildings achieve BREEAM excellent standard and everyone was clear that the project was going to give attention to sustainability. The team was aware of the objectives and the client understood that we were going to do something radical to achieve the project goals.*'

**Interviewer:** '*what did you find was the difference between this project and other conventional projects?*'

**Architect:** ‘For me, the design took longer on average I would say, with all the meetings and consultations. Trying to make sure that we listened to every idea and suggestion added about 2 extra weeks in design.’

**Project Manager:** ‘Time is valuable once any project gets underway, one extra day can add all sorts of complications. I would say we had an awful lot of meetings and emails back and forth.’

The case of the design stage lasting longer than a conventional project seems to be prevalent (Gana et al, 2017). However, the extra time spent on this stage allows all the stakeholders apply better knowledge about the building when completed.

**Interviewer:** ‘was there any research into past projects?’

**Architect:** ‘I remember we looked at different structural systems, we looked at timber frame, we looked at masonry.’

Table 1: Comparison of predicted against actual targets

Targets	Predicted	Actual
Air Permeability ( $\text{m}^3/\text{m}^2\text{h}$ )	10	Classroom: 8.48 Dining Block: 11.85
Delivered energy (Gas) $\text{kWh}/\text{m}^2$	Classroom: 47 Dining Block: 60	Classroom: 95.4 Dinning Block: 215.8
Electricity consumption ( $\text{kWh}/\text{m}^2$ )	Classroom: 34 Dining Block: 91	Classroom: 28 Dinning Block: 73.8

*The timber frame was too expensive. I think the wall build-ups were made a bit cheaper than originally designed quite a few school constructions were going on so I had a meeting with one of our partners on the project.’*

**Interviewer:** ‘Is there anything you would have done differently on the project?’

**Project Manager:** ‘The location of some of the services could have been positioned better. The conical roof was a nightmare, we did another school for the same authority two months down the road, it was curved but it was infilled with rectangle wedges, it made it so much easier. If I hadn’t been on Castle Hill we would have had the same problems.’

This is in line with the Soft Landings framework, which emphasises on the need to learn from similar past projects. The design team could look at past school and glean valuable information for the current project including the cost implication of the use of steel frames.

### ***Introduction of the end users***

The design team engaged extensively with the end users and project stakeholders. There were 12 recorded meetings between them. There was a public exhibition which attracted all groups of stakeholders. They held several consultations periodically to inform and update the end users.

**Interviewer:** ‘When were the end users introduced to the design stage?’

**Architect:** ‘we had the end users around during the briefing stage. The head teacher was at the first meeting and we had the discussion to invite the school for a brainstorming workshop.’

The engagement of the design team with the end users yielded valuable information for the team. They could go back and assess the information given to them and use that in

the design. A major example of was the agreement to shift the entrance of the site, the end users had years of experience using the school so they could provide the team with valuable information. The Architect:

*'We took feedback from the local residents and we fed it into the design. The access to the site rather than the buildings themselves. I remember there an entrance side, the railway station side and a small fire escape on the other side of the fields. We had to change that slightly to reflect feedback but the buildings didn't really change.'*

**Interviewer:** *'How did you deal with end user concerns for the project?'*

**Project Manager:** *'For this project, the end users were very involved. Some of our projects we are not fortunate to speak to actual end users. The head teacher of the school was very involved, he had a clear vision on his expectations. We spoke to teachers, students, parent representative and every meeting helped us gain new perspectives into the project.'*

*As a Project Manager, I treated the end users as team members. Their input contributed to the success of the project.'*

The words of the Project Manager indicated that the team engaged the end users and treated them as part of the design team. This according to Altomonte, et al (2015) is a formula for successful sustainable construction. The inclusion of the end users during the design stage sets the scene for collaborative working. This inclusion mentally prepares the end users and gives them a sense of ownership with the finished design (Jenson, 2011). This was true of the project because the occupants gave the highest rating to the design during the building user survey (figure 3).

The lack of a dedicated Soft Landings Champion prevented the team from profiting from a better streamlined system of meeting with the end users. The Engineer remembers a lot of unscheduled feedback from the end-users which can be a problem when assessing the comments for use. A dedicated Soft Landings Champion would have been able to specifically work on the structure of consultations and make sure that feedback did not stray to topics not needed. Although there was a lot of feedback, the Project Manager admitted that the end users had little to do with any design changes.

**Interviewer:** *'How much input did the end users have in the project?'*

**PM:** *'Well, they had little input in the building designs apart from telling us how the classrooms and playrooms were going to be used. They were particularly helpful when deciding the entrance of the site.. During the design team meetings, we discussed the points and had to decide which ones we wanted to adopt. Of course, we had to research them first.'*

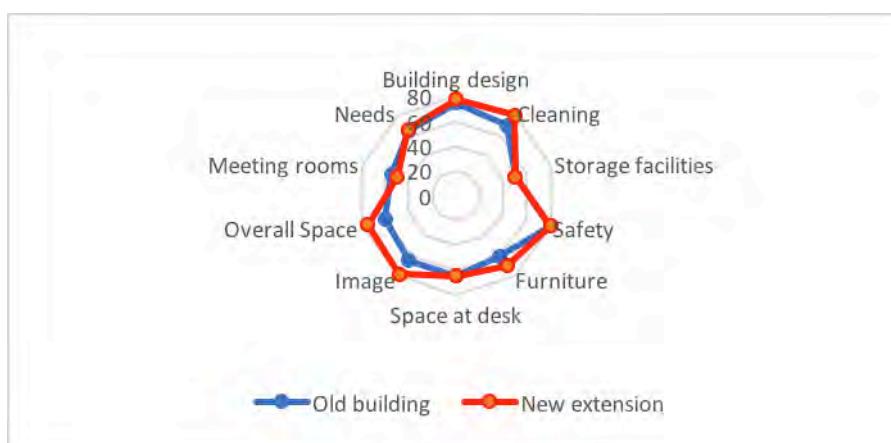


Figure 1: Percentage of user satisfaction

**Interviewer:** 'No major changes occurred because of end user participation?

**Architect:** 'None, in the building design, well just in the location of classes. The buildings were very popular with everybody we spoke to... we got really good feedback. Partly because of the curved shape of the classrooms and partly because of the barn. So it was a very popular design, there was no problem.'

Although there were no major changes because of end user participation, the workshops were classified as a success. There were suggestions from the end users that helped and informed the design. Minutes from meetings showed that the client contributed to the design by referring to equipment like extractor fans in existing buildings that were difficult to maintain and source new parts. This was noted and relayed to the M&E engineers for action. All these contributed to producing a design that was both popular and practical. Client and end user participation did present some problems as the Project Manager recalls

*'... we had some conflicting requirements during the consultations, the School wanted to have a single storey building because they were easier and cheaper to maintain. As they had some problems with replacing equipment in higher floors. While some parents and the school body preferred a storeyed building to save some space in the compound for other facilities'.*

The presence of a Soft Landings Champion would have afforded the team focus on more important aspects of the project target rather than having numerous meetings with the end users. Goldsmith and Flanagan (2017) discovered this situation as the norm with design teams actively seeking end user feedback but they are unable to convert this information into significant changes. This situation has opened an opportunity to developing a framework for user feedback.

### Information exchange

Achieving sustainable design involves collaboration between multidisciplinary teams (Bouchlaghem et al 2005, Gana et al, 2017). This is usually in the form of information flow between team members from the early stages of the project. This is important for a successful project. The Architecture has this to say

**Interviewer:** 'How often were your meetings with other teams?'

**Architect:** 'Usually, every month, well the designers will meet every 2 weeks, the meeting with the client would be once a month'.

**Architect:** *they were held in sub-groups. The clients would never meet the sub-contractors really. The clients would meet initially, they would meet the consultants always, the Project Manager and Architect, sometimes ....as well. Then when the contractor became involved, the main contractor once a month but these sub-contractors would meet the main contractor separately and sometimes the consultants would be part of that sometimes not depending on the situation.'*

From the answer above, we can deduce that there were several levels of communication going on. Each line of communication will have to be given adequate importance to avoid excluding important stakeholder or information overload. Dainty, Moore and Murray (2006) discovered that poor communication can lead to lower job performance. The information exchange does not only include communication between teams but also the timing of delivery. Good quality information will be 'the right information reaching the right person or team at the right time.'

The Project Manager on the issue of Information exchange during meetings  
*'Our meetings were organised in such a way that the activities which took longer were discussed first. So, in this case, I was in meetings with the design team a lot during the early stages. I will speak to XXXXX (name of Architect) on the phone several times a day. The meeting with the design team was once a week to check on the progress of work. Later those went to once a month or when we needed to discuss something important.'*

**Interviewer:** 'What of the sub-contractors?'

**PM:** 'We had our meetings with them once a week, in the beginning, sometimes we combined the meetings with the design team and discussed a wide range of issues especially during the thermal assessment. After that, the meetings were on need basis really.'

As with every construction project, the Project Manager recognises the benefit of giving information only when it is of importance to the receiver, as it was the case with the client and sub-contractors. Otter and Emmitt (2008), highlighted the importance of face to face meetings to review designs, share information and make decisions on their project. Stressing the situation,

*'Although team members usually work on design tasks themselves in their design offices, team communication via face-to-face communication is essential to facilitate and stimulate design processes' (Otter and Emmitt, 2008).*

The design team kept to the Soft Landings core principles by keeping the flow of information to relevant team members and making sure that the timing of the information is right by regular face to face meetings. The Engineer confirmed

**Interviewer:** 'How often were your meetings with the design team?'

**Engineer:** 'At the beginning of the project there was a lot of paper work to go through so we met nearly every day. The discussions moved on to their concepts of the design, they wanted to hear our ideas so there was a lot of brainstorming at this stage. After all the decisions were taken, our meetings tapered off to once a month. The design team could produce their drawings. We carried on our team meeting, which was usually once a week'.

## Conclusion

This paper highlights the collaborative process that is necessary for a Soft Landings project. The level of information sharing was high and frequent between all stakeholders. This does not guarantee success for the project (as seen from the missed targets in table 1) but it allows each member of the project contribute to solving the critical problems that usually arise (Gana et al, 2017). The lesson learnt from other school construction projects gave the team an advantage in the use of laminated timber frames instead of using steel. Although the project achieved its airtightness and electricity target, there were issues with the thermal comfort of the building and heat loss through the windows.

The project would have benefited from a dedicated Soft Landings champion as the feedback from the end users were not properly coordinated. The project needed to have a more effective system of cataloguing feedback for use in design. A system in which end user contribution could be classified into essential and non-essential feedback, thereby concentrating on only the essential feedback.

The implication for the design team is the understanding that engaging the end user is not enough, that a process of synthesising the feedback must be in place to take advantage of end user participation. Further research will focus on developing a communication framework that will allow design teams effectively catalogue and prioritise end user feedback.

## References

- Altomonte, S., Rutherford, P., and Wilson, R. (2015). Human factors in the design of sustainable built environments, *Intelligent Buildings International*, 7:4, 224-241, DOI: 10.1080/17508975.2014.970121.
- Axon, C. J., Bright, S. J., Dixon, T. J., Janda, K. B., and Kolokotroni, M. (2012) Building communities: reducing energy use in tenanted commercial property. *Building Research and Information*. Vol 40(4). Pp 461-472, DOI: 10.1080/09613218.2012.680701
- Bordass, B., Leaman, A. (2005). Making feedback and post occupancy evaluation routine 1: A portfolio of feedback techniques. *Building Research and Information*. Vol 33 (4). Pp 347-352.
- Bouchlaghem, D., Shang, H., Anumba, C., Cen, M., Miles, J. and Taylor, M. (2005). ICT-enabled collaborative working environment for concurrent conceptual design. *Architectural Engineering and Design management*. Vol 1(4). Pp 261-280. Doi: 10.1080/17452007.2005.9684597
- Building Data Exchange (2014). Building Performance Evaluation. Prepared for Innovate UK. Available at [www.buildingdataexchange.org.uk](http://www.buildingdataexchange.org.uk). Accessed: January 2017
- Burnett, J. (2007). Sustainability and sustainable buildings. *International Journal of Hong Kong Institution of Engineers Transactions*. Vol 14 (3). Pp 1-9.
- Dainty, A., Moore, D., & Murray, M. (2006). *Communication in construction – Theory and practice* (1st ed.). London: Taylor and Francis.
- DfES. (2006a). *Schools for the future: Design of sustainable schools: Case studies*. London: The Stationery Office.
- Fedoruk, L. E., Cole, R. J., Robinson, J. B., Cayuela, A (2015). Learning from failure: understanding the anticipated-achieved building energy performance gap. *Building Research and Information*, Vol 43 (6). Pp 750-763.
- Flyvbjerg, B. (2006). Five misunderstandings about Case-Study Research. *Qualitative Inquiry*. Vol 12 (2), 219-245 doi:10.1177/1077800405284363.
- Gana. V., Giridharan. R., and Watkins. R. (2017). Application of Soft Landings in the Design Management process of a non-residential building. *Architectural Engineering and Design Management*, Vol. Pp 1-16
- Goldsmith, W. Flanagan, T. (2017). Value methodology- case studies with climate resilience and sustainability policy application. *Architectural Engineering and Design Management*. Vol 13 (1), Pp 3-21.
- Gupta, R. and Gregg, M. (2016). Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilized institutional building in the UK. *Energy and Buildings*. Vol 128, Pp 68-80
- Jensen, P. A. (2011). Inclusive briefing and user involvement: Case study of a media centre in Denmark. *Architectural Engineering and Design Management*, 7(1), 38–49. doi:10.3763/aedm.2010.0124.
- Leaman, A. Stevenson, F. & Bordass, B (2010). Building evaluation: Practice and Principles. *Building Research and Information*. Vol 38 (5), Pp 564-577
- Moncaster, A and Simmons P. (2015). Policies and outcomes for UK sustainable schools. *Building Research and information*. Vol 43 (4), pp 452-464.
- Otter, A. D, and Emmitt, S. (2008). Design team communication and design task complexity – The preference for dialogues. *Architectural Engineering and Design Management*. Vol 4 (2) Pp 121–129.
- Usable Building Trust and BSRIA. (2014), The Soft Landings Framework: For better briefing, design, handover and building performance in use. BSRIA BG 54/2014. Building Services Research and Information Association, Bracknell.
- Usable Building Trust and BSRIA. (2014), The Soft Landings Core Principles. BSRIA BG 38. Building Services Research and Information Association, Bracknell.
- Way, M and Bordass, B. (2005). Making feedback and post-occupancy evaluation routine 2: soft landings- involving design and building teams in improving performance. *Building Research and Information*. Vol 33, (4). Pp 353-360
- Yin, R. (2003). Case study research: Design and Methods, 3<sup>rd</sup> edition, London, SAGE Publications.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Temporal Indoor Overheating risk management challenges for free-running spaces: Highlighting the demand functions for decision-support

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**Abstract:** A key question with regards to managing indoor overheating risk is: In the current carbon constrained environment, what is the most effective design or space use strategy? Although there exists numerous passive techniques to reduce indoor overheating instances, the decision-making process of appraising these tactics, at the various decision-making stages of a building's lifetime, remains a challenging task. This is true especially when making decisions for heterogeneous urban landscapes, while considering the effects of time frame uncertainty. In this paper, an empirical study has been undertaken to characterise practical decision-making challenges incurred when managing temporal indoor overheating risk. The study discusses results from real-time indoor thermal monitoring carried out using digital data loggers in free-running office spaces in 30 different buildings in Nairobi-Kenya, for the period between 2008 and 2015. The trend of indoor overheating in these spaces has been reviewed, as well as a comparison made between building attributes with the corresponding indoor overheating risk levels. The review implicates a need to clarify and make transparent both factors and information that shape the form and content of decision support when managing temporal indoor overheating. Three demand functions of decision-relevant information, presented alongside overarching goals for managing indoor overheating risk, have been conceptualised.

**Keywords:** Indoor overheating risk, Thermal comfort, Temporal decision-making,

### Introduction

Existing definitions and insights into overheating<sup>1</sup> outline three main factors that shape its outcome: 1) The technical aspects of a building's design and the occupancy patterns of its occupants; 2) The building's response to the prevailing climatic conditions and its Urban context; and 3) The assumptions about occupant(s) thermal comfort threshold. From the outlined descriptions of overheating, it is evident as well that emphasis has been laid on two key factors that characterise occupants' thermal comfort assumptions. One factor being the upper benchmark or threshold temperature limit beyond which a person can express their dissatisfaction with the thermal environment. The second factor is the length of time of

<sup>1</sup> Anastasia et al (2015, p.3) have defined Overheating as "The phenomenon of a person experiencing excessive or prolonged high temperatures within their home, resulting from internal and/or external heat gains, and which leads to adverse effects on their comfort, health or productivity". Overheating phenomenon has also been "generally understood to be the accumulation of warmth within a building to an extent where it causes discomfort to the occupants". (NHBC, 2012, p.1). Further, CIBSE TM36 (2005) has summarised overheating as: "When the benchmark temperature is exceeded, the building is said to have 'overheated' and if this occurs for more than the designated amount of time, the building is said to suffer from 'overheating'."

thermal discomfort is sustained above the threshold temperature. It can then be argued here then that the measured understanding of overheating can be expressed as the departure from an upper thermal comfort threshold of an occupant, both in magnitude and length of time of discomfort, for any given space. Taken together, these dimensions define the **vulnerability** level of a free-running<sup>2</sup> space to indoor overheating. Depending on the resultant level of vulnerability of such a space to overheating, a **response** to overheating is elicited, comprising acceptance and/or heat mitigating action. Risk theory terms the latter efforts as a form of risk management<sup>3</sup>. In this case, these efforts could be in the form of seeking the best possible adaptive opportunities a space has to offer and/or the need to work out a preparedness plan in case of future thermal discomfort.

The outlined understanding of indoor overheating risk management depicts it as a decision-making exercise. An exercise that is accompanied by the need to meet a certain level of thermal comfort expectation that is to be considered alongside other values and ambitions of the built environment decision-making stakeholders. This measured understanding of indoor overheating risk characterization has been adopted in this paper to paint a clearer picture of practical decision-making challenges incurred when managing both existing and future indoor overheating risk in a case study area of Nairobi. Results from real-time indoor thermal monitoring carried out using digital data loggers in free-running office spaces in 30 different buildings in Nairobi, for the period between 2008 and 2015 have been discussed. This monitored data has been translated to indoor overheating risk assessment. The question on how to manage whole-life thermal performance in free running spaces, while accounting for both variation and uncertainty in the short and long-term future has been explored. Ultimately, implicating the need to clarify and make transparent both factors and information that shape the form and content of decision support<sup>4</sup> when managing temporal indoor overheating. Three demand functions of decision-relevant information have been conceptualised and presented alongside overarching goals for managing indoor overheating risk.

### **Temporal Indoor overheating risk management challenge: A case for Nairobi-Kenya**

Nairobi experiences tropical warm climatic conditions all year round, and as a result, indoor overheating challenges underlie a considerable portion of existing buildings. Added to that, the diversity of Nairobi's non-domestic building stock and its cosmopolitan nature presents wide-ranging thermal comfort expectations and associated building adaptation decision-making challenges. Currently, no legislation governs building design in relation to climate in Kenya. This lack of clear bio-climatic design guidelines has partly contributed to the variety of building styles cropping up in the country and particularly in Nairobi, over the years expressing a range of worldwide influences and building styles. A few that have outstanding passive design strategies fit for a low latitude tropical climate, some illustrated in Figure 2, while quite a number of designs, on the other hand, have had their mistakes cushioned using very energy intensive means to afford their occupants favourable indoor thermal comfort.

<sup>2</sup> The term "free running" in this paper applies to a building which is neither mechanically heated nor cooled.

<sup>3</sup> Risk Management has been defined as "coordinated activities to direct and control an organization with regard to risk" ISO 73:2009

<sup>4</sup> Decision support has been defined as "a set of processes intended to create the conditions for the production of decision-relevant information for its appropriate use" .(IPCC, 2014, p. 202)

Various scholars in Nairobi have investigated the indoor thermal performance of some relatively well-performing buildings over the years under different theses with varying research objectives. (Loki, 2009; Njeru, 2008; Gichuyia, 2010; Nyole, 2011; Deogun, 2011; Njoroge, 2012; Kuria, 2012; Nyole, 2015; Njoroge, 2015; Mworia, 2015) These studies are seen to have a common theme of establishing the trend of the indoor thermal performance of free-running buildings investigated, and in addition, they have attempted to compare building design and use attributes with the corresponding indoor thermal performance, endeavouring to inform current practice. Some of the buildings studied over the years and which are the subject of inquiry in the section below are presented in Figure 2.

### **Real-time indoor overheating results of some monitored office buildings in Nairobi**

Figure 1 presents the quantified indoor overheating risk results from the real-time indoor thermal monitoring carried out using digital data loggers in 30 different buildings in Nairobi, for the period between 2008 and 2015. To be noted here, all spaces investigated are not mechanically cooled with the exception of House of Van-Guard whose indoor temperature readings were used to establish an acceptable upper level of thermal comfort threshold, which averaged at 24.4°C. Based on this, a major assumption has been made in the calculation of indoor overheating levels in this paper, that once indoor temperature threshold of 25°C has been exceeded, the space monitored is said to have overheated. This provided a general criteria for identifying an upper limit of thermal discomfort for these preliminary evaluations. Indoor overheating has been calculated using the degree-hour criterion (Carlucci & Pagliano, 2012), a cumulative index employed to quantify the average daily accumulation of indoor overheating for each space investigated. The amount by which the indoor temperature for every given hour monitored exceeds 25°C was calculated for each space. The hourly values of indoor temperature above this thermal comfort threshold were then calculated per hour for each day, and the net value of thermal discomfort in degree centigrade hours (°Ch) was then tabulated. This was then averaged per day for comparative analysis purposes, as the total number of days of indoor temperature monitoring in the spaces investigated differ (Figure 1).

### **IOR results highlighting the demand functions for decision-relevant information**

Despite the relatively small pool of non-domestic spaces investigated, which are by no means representative of the entire non-domestic building stock of Nairobi, there is significant evidence of **heterogeneity**, illustrated by the clear differences in building characteristics (Figure 2). This has been characterised by the variety of building forms, facade design styles and building materials used, in addition to the different urban contexts and boundary conditions around the individual buildings. Consequently, how these building-related features combine at varying magnitudes and frequencies in the spaces monitored and time slot considered resulted into a relatively broad spectrum overheating output that ranged from 0°Ch/day to 64.17 °Ch/day for the non-air-conditioned spaces. This varying range of overheating levels was not only true across all spaces monitored but was also inherent in each of the spaces as elaborated below, in the case of:

- a) The same space monitored on consecutive days: A closer look at the daily indoor temperature profiles for each space monitored indicates the lack of a typical daily thermal profile in most of the spaces monitored. In only a few cases is this variation of temperature subtle, as was in the case of FCC, which recorded an almost constant temperature of 21°C during the days of monitoring. The only other two cases were KRHq. and the ADD buildings.

b) The same space monitored in different months/years: GEM, BS, and OM buildings are good examples illustrating this variation. The three spaces in each of these buildings were monitored in October 2009 and again in April 2010, and thermal logged at exactly the same time in both instances. Yet, OM seems to rank lowest in indoor overheating in April 2009 and rank highest in overheating levels in October 2010 among the three buildings. It could be argued here that all factors constant, the thermal performance rankings would have remained the same in both instances but that was not the case.

c) Further evidence of indoor overheating variation can be seen in the case of the same space monitored in different zones as exemplified in the case of CUEA Lib. The reading space in the reading carrels recorded 0.8°CCh/day of overheating while the reading space near the atrium recorded 0°CCh/day overheating, although the two spaces were monitored at the same time and in the same open space, a few metres apart. The case of TPT is a similar example where spaces in its 1st floor, 5th floor, and its 13th floor, were monitored at the same time but had their overheating levels relatively varied, at 3.6°CCh/day, 4.74°CCh/day and 7.29°CCh/day respectively.

Taken together, this variation in thermal performance exemplified above for each space, both at an hourly, daily, weekly, monthly and yearly scale, grounds the view that **each space comprises a heterogeneous compilation of character over a given length of time**.

The two spaces logged in SA and KEMU buildings recorded the highest IOR level. These spaces had their indoor temperatures way above 28°C for a relatively long time and went on to record indoor temperature highs of 41.52°C and 32.03°C respectively. The question on **what are the building and/or use related attributes that contributed the most to this high indoor overheating risk** becomes fundamental here. What is apparent from the two buildings, is that they have in common a relatively high window to wall ratio of 100% Curtain walling. Although SA has a ring of 600mm deep spandrels running around its West facing facade, the logged space was in the curved glazed part of the building that is not shaded. Based on this and the fact that they share similar building use attributes, there is a compelling reason to argue that the high window to wall ratio or the curtain wall glazing used could have been responsible for the high indoor overheating levels in both cases. However buildings including LH, BS, GEM, GBP all have a similar 100% external curtain walling, and yet they recorded relatively better thermal performance.

Along the same lines, there is a presupposed argument by various scholars in this region that since the advent of the use of extensive curtain walling with less sun-shading strategies from the 1980's onwards the risk of indoor overheating has become higher. Nyole (2014) in her dissertation investigating the role of the building envelope in ensuring internal thermal comfort levels are achieved, went on to investigate four buildings with the varied use of curtain walling. The four buildings which included the CCK, GBP, CBA and DL buildings had spaces in their western facades monitored at the same time. From the results, also included in this study, one would expect the CCK building with the least window to wall ratio and most sun-shading strategies comparatively to have performed better based on this argument, but the IOR results contradict this prevailing view. Sun-shading strategies have been recommended as some of the most favourable strategies for cutting substantial solar gains that occur directly through window transmissions and indirectly from hot surface conditions and radiation for this type of climate as cited earlier. The question on **What is the measured reduction in indoor overheating offered by each building design and user strategy in singularity** becomes important here. That is, considering spaces like GWML and CH with significant use of sun shading on their building envelopes, yet none of the two

recorded zero overheating levels. **This is a clear indicator that the ranges, magnitudes, and frequencies of other building design and use attributes are a major factor in the overall indoor thermal performance of space.**

Following closely regarding relatively high indoor temperatures were spaces monitored in the KNA building, UNON and 3rd floor CCK buildings, whose indoor temps were mostly above 25 °C at the time of monitoring, with highest indoor temperatures recorded at 27.51°C, 31.52°C, 32.76 °C for each building respectively. These three particular buildings have been acclaimed for their application of innovative passive design strategies (Loki 2009). Just by reviewing the technical aspects of their built form, facade design, building envelope treatment, thermal properties of building materials used, there is a relatively high level of thermal performance expectation. **Thermal performance expectation seems to differ from the measured reality** here as one would expect that spaces monitored in these three buildings would have lower overheating risk levels compared to spaces in for instance: GEM, BS, and CT that have lower ranking climate responsive technical aspects. However, to be noted here is that the logged spaces are not a representation of the thermal performance of all spaces in the entire building.

An even higher level of thermal performance expectation was placed on spaces logged in the OM building and particularly the award-winning CCHq. building, based on their impressive passive design strategies. The CCHq. building, for instance, boasts of a myriad of features that make it a truly unique building. This is shown by its solar shading style where all north facing windows are inset in its relatively thick external wall creating a box profile that further provides self-shading, and includes the additional solar shading ring louvres running around its North facing wall. This is in addition to its light coloured, and relatively thick external wall with relatively high thermal mass; Its south facing curtain wall is shaded using a relatively deep crescent shaped canopy; A green roof garden that acts as a recreation area and ensures that there is minimal heat gain into the building through the roof top; The use of undulating earth mounds on its grass-covered landscape, helps conceal the half basement parking and partly shades the ground floor direct sun rays. This is to mention just but a few external physical aspects. More can be said about its built form configuration and orientation as well as its ventilative cooling strategies. Based on the scientifically understood principles of all the strategies it has in place, one would expect its spaces to be at zero risk of indoor overheating and no chance of the use of mechanically cooled spaces. On the contrary, the building has quite a number of air-conditioning units installed to support cooling of the spaces (Gichuyia 2012). This then begs the questions on **how much is enough design effort without over-providing or under-providing for thermal comfort? Are building use parameters the more prominent risk factors to indoor overheating in passively designed spaces?** How did spaces monitored in CUEA, UF, Add, CM achieve the optimum combination of building design and use attributes, having recorded zero overheating risk levels? Moreover, is the ultimate question of: Even after achieving that optimal combination of building design and user related attributes that ensure a space has a low overheating risk in the current context, **how do we ensure that these strategies stand the test of time? Especially in a future where the climate, boundary conditions around the building, modification of the space and its use are not likely to remain stationary?**

## Discussion

Based on the above frame of reference, there is a glaring resolve that just the understanding of scientifically understood principles of achieving thermal comfort in their

detached singularity is not enough information for decision support. However, to appraise and adjudicate between the numerous heat mitigating decision options, a review of all the intersecting components of causal factors of the external climate, building related attributes, assumptions about thermal comfort thresholds, alongside passive heat mitigating interventions at varying frequencies and magnitudes over time, is necessary. Such a review would need to accommodate the three different dimensions of capacity needs of risk management as discussed by Cardone et al. (2012) that can be differentiated as 1)Capacity to anticipate indoor overheating risk, 2)Capacity to respond to indoor overheating risk, and 3)Capacity to recover and change from indoor overheating risk (Table 1). A review, cutting across all three dimensions, would require means of uncovering the dynamic complexities of the cause-vulnerability-response interactions of the thermal space variables under conditions of diversity. Diversity in this case capturing the effects of heterogeneity and uncertainty brought about by the rich array of building styles and space use characteristics on the one hand, and the highly unpredictable world on the other.

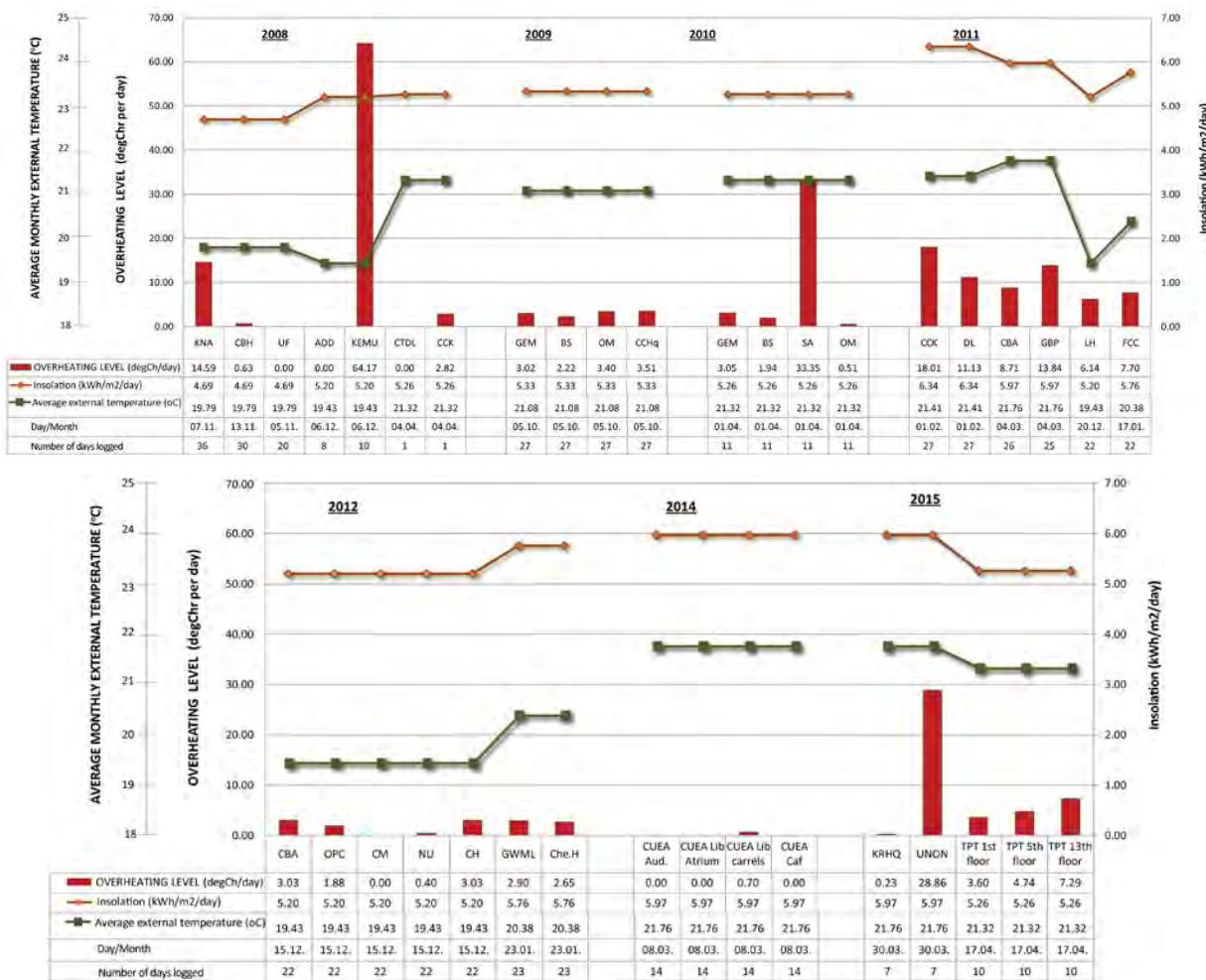


Figure 1: A summary of results from the real-time indoor thermal monitoring carried out using digital data loggers in the non residential buildings in Nairobi (Figure 2).

BUILDINGS MONITORED			
COCACOLA HEADQUARTERS (CCHQ) = 27600	KENYA NATIONAL ARCHIVES (KNA) = 37600	UNEP HEADQUARTERS - GIGI (UNEP Hall) = 18600	CITY MARKET (CM) = 18600
NORWICH UNION (NU) = 11,900	CONSOLIDATED BANK HOUSE (CBH) = 14,600	KENYA RAIL WAY HEADQUARTERS (KRRHQ) = 17,600	GEMINI OFFICES (GEM) = 17,600
CORNER HOUSE (CH) = 11,900	UFUNGAMANO (UF) = 2,600	TELEPOSTA TOWERS (TPT) = 27,600	OLD MUTUAL OFFICES (OM) = 18,600
CUEA AUDITORIUM (CUEA Aud) = 1,600	AAU UNIVERSITY OF NAIROBI (AAU) = 5,600	TELEPOSTA TOWERS (TPT) = 27,600	SHELTER AFRIQUE OFFICES (SA) = 1,600
CUEA LIBRARY (CUEA Lib) = 1,600	KENYA METHODIST UNIVERSITY (KEMU) = 7,600	TELEPOSTA TOWERS (TPT) = 27,600	DELOITTE NAIROBI OFFICES (DL) = 1,600
CUEA CAFETERIA (CUEA Caff) = 1,600	CITADEL OFFICES (CTOL) = 3,600	FRENCH CULTURAL CENTRE (FCC) = 3,600	COMMERCIAL BANK OF AFRICA OFFICES (CBA) = 1,600
GANDHI WING MEMORIAL LIBRARY (GWML) = 6,600	COMMUNICATIONS COMMISSION KENYA (CCK) = 3,600	LONRHO HOUSE (LH) = 12,600	GATEWAY BUSINESS PARK OFFICES (GBP) = 12,600
CHESTER HOUSE (CH) = 12,600	BLUESHIELD OFFICES (BS) = 14,600	HOUSE OF VANGUARD (HoV) = 3,600	OLD PC HOUSE (OPC) = 1,600

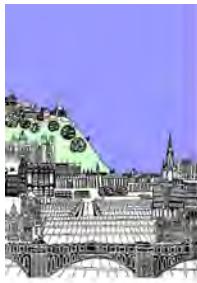
Figure 2: A pictorial coverage buildings thermally monitored with results presented in Figure 1

Table 1: Table highlighting three main demand functions of decision-relevant information necessary for managing indoor overheating risk as drawn out from the Nairobi case study.

Demand functions for decision-relevant information	Corresponding questions posed in the case of Nairobi
<b>Capacity to Anticipate</b> Actions that take into account the cause and effects impacts of risk, towards risk prevention (Cardona et al., 2012, p.74)	a) How to anticipate for the range of possible overheating due to factors of heterogeneity and uncertainty. What are the building and/or use related attributes that contribute the most to indoor overheating risk? b) How do we achieve the optimum combination of building design and use attributes, that ensures zero overheating?
<b>Capacity to Respond</b> Actions necessary to react in the event of a risk, while accounting for the vulnerability to risk and the ability to offset this. (Cardona et al., 2012, p.74)	a) What is the measured reduction in indoor overheating offered by each building design and user heat mitigation strategies? b) How much is enough design effort without over-providing or under-providing for thermal comfort?
<b>Capacity to recover and change</b> Actions that push the recovery from risk towards a transformation of systems to effect lasting responses that look to avoid vulnerability (Cardona et al., 2012, p.75).	a) How to manage thermal performance expectation gaps from the measured reality? b) How do we ensure that these strategies stand the test of time? Especially in a future where the climate, boundary conditions around the building, modification of the space and its use are not likely to remain stationary?

## References

- Anastasia, M., Mavrogianni, A., Davies M.(2015). Defining Overheating - Evidence Review. London, UK. Retrieved from: <http://www.zerocarbonhub.org/sites/default/files/resources/reports>
- Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F., Sinh, B.T., Décamps, H. and Keim, M. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Determinants of Risk: Exposure and Vulnerability.
- Carlucci, S. & Pagliano, L.(2012). A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. Energy and Buildings, 53, pp.194–205.
- CIBSE TM36.(2005). Climate Change and the Indoor Environment: Impacts and Adaptation—CIBSE TM36. CIBSE, London.
- Deogun, I.(2011). Eco-architecture: A Case of Nairobi, Kenya. Undergraduate dissertation. UON.
- Gichuyia, L.(2010). The impact of buildings on climate change: A case of Nairobi's Upper Hill area; towards low energy Architecture. Undergraduate dissertation. The University of Nairobi.
- Gichuyia, L.(2012). The implication of global warming on the indoor thermal performance of free-running office buildings in Nairobi - Kenya. MPhil dissertation. The University of Cambridge.
- Mworia, J.(2015). Teleposta towers case-study. Masters dissertation. The University of Nairobi.
- Kuria, E.(2012). Biomimicry: An approach to Environmentally Conscious design. Undergraduate dissertation. The University of Nairobi.
- Loki, D.(2009). Passive & low energy building design in Nairobi: Building Design Strategies for Thermal comfort, Day-lighting & Natural Ventilation in Nairobi's Tropical Upland Climate. Undergraduate dissertation. The University of Nairobi.
- NHBC. (2012). Understanding overheating – where to start: An introduction for house builders and designers. for the NHBC Foundation by Richards Partington Architects (N.F.44), Milton Keynes, UK.
- Njeru, P.(2008). Investigating Thermal Comfort in Urban Transitional Spaces. MPhil dissertation. The University of Cambridge.
- Njoroge, B.(2012). Nairobi architecture in a climate of change; A Study of the evolution of the carbon footprint of buildings in Nairobi CBD and Upper Hill area. Undergraduate dissertation. The University of Nairobi.
- Njoroge, B. (2015). Towards a climate-responsive architecture: A Sensitivity Analysis of Passive Design Strategies for a free-running building in Nairobi. MPhil dissertation. The University of Cambridge.
- Nyole, F.(2011). Emerging trends in building envelope technologies: A Thermal Comfort Analysis for Nairobi. Undergraduate dissertation. The University of Nairobi.
- Nyole, F.(2015). The use of construction technology to enhance the living environment and ensure minimal disturbance to the ecology. A case of Nairobi, Kenya.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainability performance tracking of social housing: the tale of two projects in Brazil

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**Abstract:** A number of mandatory and voluntary 'sustainability' rating systems emerged over the past twenty years. However, they are usually restricted to environmental assessments carried out at individual buildings scale, which seems to be inappropriate to capture and describe environmental, economic and social challenges faced in social housing development contexts. Assessments should be adapted to neighborhood scale and local conditions, and involve residents in the process. Against this backdrop, this paper aims at verifying sensibility and adequacy of two rating systems - Selo Casa Azul (Brazil) and Housing Quality Indicators, Hqi (UK) - to assess two selected Brazilian social housing developments. Casa Azul was applied to both projects, whilst Hqi required detailed information only available for one of them. Our results suggest that Casa Azul is insensible to distinguish performances, despite having been developed to assess Brazilian residential projects, including social housing. Hqi also has points not applicable to our cases, for either not have been designed for social housing application or for not admitting adjustments to contexts other than the original British conditions. Combination of features from different systems seems promising to meaningfully consider sustainability performance aspects and allow for reflection and improvement of such design models.

**Keywords:** social housing, sustainability assessment, Selo Casa Azul, Housing Quality Indicators

### Introduction

Sustainability assessment tools have been recurrently used to monitor building performance and success of public and sectorial initiatives and policies. Such tools follow a common overall content and structure, however no similar consensus regarding scope and, particularly, assessment procedures seem to exist. Most assessment systems still focus on environmental aspects and ignore social and economic issues which are relevant for developing countries, and often do not integrate stakeholders in tool development and feedback processes (Sharifi and Murayama, 2013), which can be specially critical for social housing projects.

Social housing (SH) developments typically implemented with public funding to reduce housing deficit, and targets low income, socially vulnerable and education-deprived population. Demand for this housing model is especially high in developing countries or in areas devastated by natural or environmental disasters. Developments frequently deliver thousands of housing units at once, which virtually shapes new neighbourhoods or even towns. Assessment scope therefore extrapolates the building scale and also demands examination of neighbourhood scale (Berardi, 2011; Sharifi and Murayama, 2014) and local conditions (Retzlaff, 2009). To involve and deliver meaningful actions to future dwellers,

development of assessment tools would benefit from embracing participative approaches (Sullivan and Ward, 2012).

In this paper, we aimed at analysing two housing assessment systems, devised in different background contexts, regarding their comprehensiveness and sensitivity to distinguish projects' performance on important sustainability aspects. In particular, we checked for uncovered sustainability aspects relevant to SH, adequacy to mixed scales, and adaptation to local context.

## **Method**

In this study, two tools - Selo Casa Azul (Brazil) and Housing Quality Indicators, HQI (UK) - were selected to assess sustainability of Brazilian social housing developments: 'Project Várzea', a development in early design stage in Rio de Janeiro state, and 'Paraisópolis Condominiums E and G', a favela development certified at Casa Azul's highest level. Casa Azul assessments were carried out for both developments; whilst information available on 'Paraisópolis' was insufficient for performing HQI assessment.

### ***Selected developments***

#### ***Project 'Várzea que Queremos'***

'Project Várzea' is a partnership between private contractors and the municipal administration of Niteroi, in Rio de Janeiro state, funded by the federal housing program 'Minha Casa, Minha Vida, MCMV' ('My House, My Life'). The project will be built in a redevelopment area located 25 Km from downtown, adjacent to the State Park 'Serra da Tiririca', fully preserved on the project. The neighbourhood has one municipal and eight intercity bus lines, five public schools, a day care centre and two hospitals in a three-kilometre radius.

Design (Figure 1a) is currently in conceptual design stage and aims at reducing parking area, while providing broad access to public spaces and leisure areas, universal design, and green streets. Only 20% of the assigned land was parcelled to accommodate seven condominiums with individual leisure areas. Residential lots occupation is below 22%, and total residential building footprint is less than 5%. A total of 2,020 housing units (HUs) complies with monthly income ranges for MCMV Program track 1 (0 to 3 minimum wages) and track 2 (3 and 6 minimum wages). Track 1 HU areas are 42.90 m<sup>2</sup> (two bedrooms, living room, kitchen, service area, and bathroom). Track 2 HUs have 47.65 m<sup>2</sup> and include a little balcony. Complete infrastructure is provided, encompassing pedestrian lanes, street network, transportation modes and demand management, bikeways, bus station, and use diversity in the development's centre (commerce, leisure, sports, schools, institutional, cultural, health, and social equipment).

Main concepts emphasise recovering degraded areas, reducing dependency on motor vehicles, and preserving habitat, wetland and water bodies. To achieve these aims, Project Várzea applies the Transit-Oriented Development (TOD) principles and guidelines from two Brazilian sustainability-related certifications: 'Procel-Edifica energy-efficiency label' and 'Selo Casa Azul'.

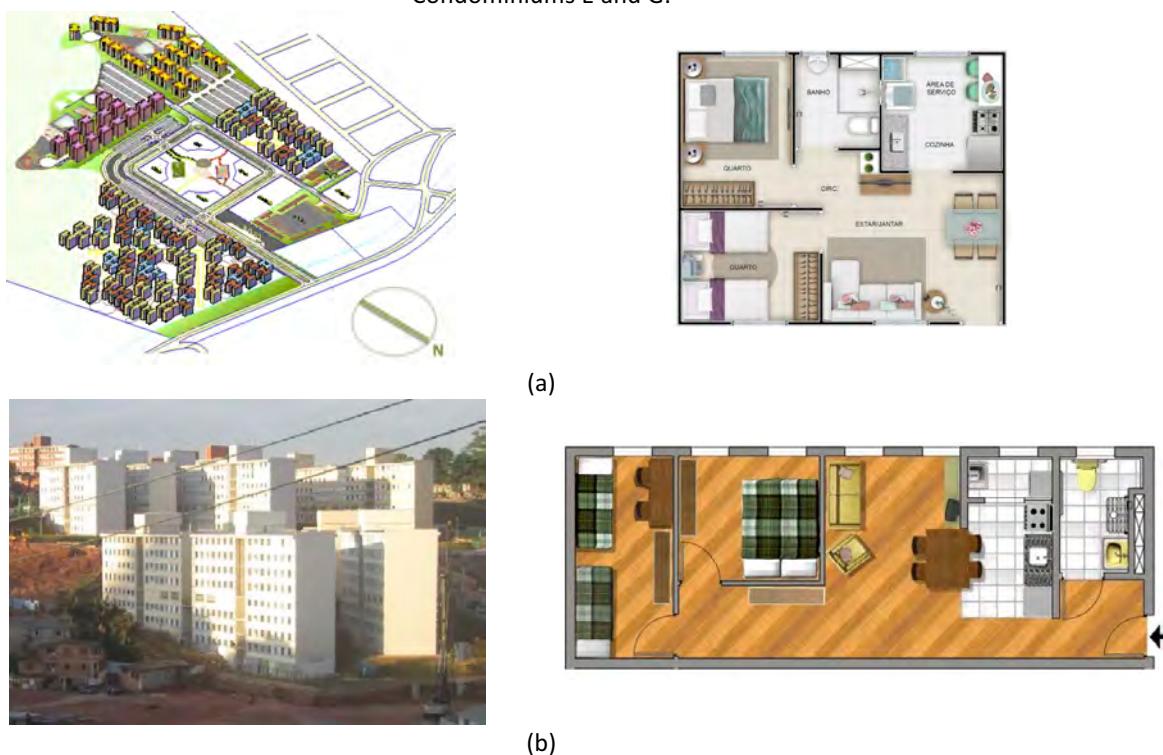
TOD focuses on integrating sustainable transport and land use. It can be used both as *guidance* for creating laws to urban design, transportation design, land use and parking lots, and as *assessment* at planning or design stage of conditions for creating walkable

communities; prioritizing use of bicycles over cars; creating dense and connected road networks; increasing population density in areas with greater capacity for public transport stations to increase efficiency; arranging regions according to job offer to decrease travel time and needs; promoting changes that encourage the use of public transport, cycling and walking; and encouraging diversified activities through mixed use (ITDP, 2014).

Procel-Edifica was launched in 2009 by the Brazilian Energy Ministry as part of the National Program for Energy Conservation to assess performance of office and residential buildings regarding energy efficiency, natural ventilation, indoor environmental comfort and accessibility (Gonçalves, 2016).

Selo Casa Azul ('Blue House Label') is a voluntary rating scheme developed by an expert group for Caixa Econômica Federal (CEF), the largest public housing financing bank in Brazil. Casa Azul was launched in 2010 to acknowledge housing developments that adopt more efficient solutions related to buildings construction, maintenance, use and occupation. It was the first rating tool completely developed for the Brazilian context, and can be used by construction companies, public authorities, public companies, housing cooperatives, associations and social movements entities during the feasibility stage. Casa Azul is applicable to any development eligible for the CEF financeable portfolio, and provides guidance for more sustainable housing projects, from establishing partnerships between the bank and project proponents.

Figure 1. Site view/plan and respective HU layouts of (a) 'Várzea que Queremos' and (b) 'Paraisópolis' Condominiums E and G.



#### *Project Paraisópolis - Condominiums E and G*

Ten Brazilian developments achieved Casa Azul certifications, being one of them labelled as silver and the remaining certified at gold level. Paraisópolis Condominiums E and G (Figure 1b) achieved the highest score among the gold-certified projects. 'Paraisópolis' is a favela located 15 kilometres away from the centre of São Paulo, which went through several urbanization interventions over the past years. As part of this process, important public

facilities were installed within its boundaries or nearby, like the ‘Social Pavillion’, the ‘Sanfona Park’, which permeates the complex, and the ‘Grotão Music Factory’. At medium distance, is located the Monotrail ‘Paraisópolis’, and a little farther away is the ‘Córrego Colombo Linear Park’. The neighbourhood also counts on mobility, green, public transport, and centralities networks. Also as part of the urbanization interventions, the Housing Secretary of São Paulo built the ‘Paraisópolis’ Complex’ in 2012, a set of seven condominiums. Condominiums E and G have, respectively, 127 and 44 housing units (HUs), with 50 m<sup>2</sup> each, composed by two bedrooms, living room, kitchen, service area, and bathroom; equipped with individual metering of gas and water. The common staircases are day lit, and each condominium has an open patio and a small equipped playground. Community participated in the design and construction process through social inclusion actions and work with local leaderships, important aspects of Casa Azul social sustainability goals. During construction, selective waste collection kits were distributed along the construction site to facilitate and ensure correct waste management and destination by licensed companies. Construction workers and future residents had environmental education training. Future dwellers also received capacity building program for adequately managing and maintaining the implemented features.

### ***Selected assessment tools***

#### ***Selo Casa Azul***

Casa Azul requires compliance to the Brazilian accessibility standard and has 19 mandatory and 34 free-choice criteria divided into six categories (John and Prado, 2010). Projects that comply with mandatory criteria only are rated ‘Bronze’, while higher ratings vary with the the number of free-choice criteria met: ‘Silver’ (minimum of 6 free-choice criteria) and gold (over 12 free-choice criteria).

Table 1. Selo Casa Azul categories and criteria. Source: (John and Prado, 2010)

Categories	Criteria
Urban quality	Quality of the environment – infrastructure*; Quality of the environment – impacts*; Improving the environment; Rehab of degraded areas; and Rehab of buildings.
Design & Comfort	Landscaping*; Flexible design; Community interrelation; Alternative transportation; Collection of use recyclables*; Recreational equipment*; Thermal performance – envelope*; Thermal performance – orientation*; Daylighting – common areas; Ventilation & daylighting – bathrooms; and Adaptation to local topography.
Energy efficiency	Efficient light bulbs – private areas**; Occupancy sensors – common areas*; Solar heating system; Gas heating system; Individual gas metering*; Efficient elevators; Efficient appliances; and Alternative energy sources.
Material resources	Modular design; Quality of materials and components*; Industrialized or prefabricated components; Reusable molds and anchors*; Construction and demolition waste (CDW) management*; Optimized concrete mix; Use of low-clinker cement types CIII and CP IV; CDW pavement; Durability of facades; and Use of certified wood.
Water management	Individual water metering*; Dual flush devices*; Water efficient devices – aerators; Water efficient devices – flow regulators; Rainwater harvesting; Stormwater retention; Rainwater drainage; and Permeable area*.
Social practices	Education for CDW management*; Employees’ environmental training*; Employees’ personal development; Employees’ professional training; Inclusion of local workers; Community’s participation in the project design; Orientation to the new residents*;

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Residents' environmental training; Capacity building for entrepreneurship management;  
Actions for social risk mitigation; and Actions for employment and income generation.

\* Mandatory criteria

\*\* Mandatory criteria for MCMV Track 1 projects

### *Housing Quality Indicators*

Housing Quality Indicators (HQI), launched in the 1990s, was created to incorporate quality as assessment criterion of housing financed by the UK Department of the Environment, Transport and the Regions' Housing Corporation. This system was developed to ensure housing adequacy to laws and included aesthetic quality as an essential issue. Over a trial period it was transformed into a flexible tool that can be used in any project phase, by consumers and developers, for new buildings or retrofits, public or private buildings, isolated units or mixed housing types. It is currently used by the Housing Corporation as a screening tool for financing approvals (Harrison, 1999).

The scope of its fourth and latest version (2008) is divided into two parts - form and spread sheet - comprising three main categories: location, design and performance. The form collects information regarding project description and ten indicators: 1. location; 2. site – visual impact, layout and landscaping; 3. site – open space; 4. site – routes and movement; 5. unit – size; 6. unit – layout; 7. unit – noise, light, services and adaptability; 8. unit – accessibility within the unit; 9. unit - sustainability; and 10. external environment – Building for Life. The Building for Life criteria is an external assessment composed by 20 criteria covering four themes: 1. character; 2. roads, parking and walkability; 3. design and construction; and 4. environment and community. Finally, the spread sheet converts the collected answers into points, which demonstrate the project's performance according with each indicator. All indicators are considered equally important for quality, but users can change weighting according to regional priorities (Harrison, 1999; The National Affordable Homes Agency, 2008).

### **Results and Discussion**

'Project Várzea' Casa Azul assessment profile (Table 2) differs from Paraisópolis in only seven items, despite important differences in concepts and contexts. As for urban quality, both projects reached the performance same criteria, and only failed to meet building rehab requirement. Both projects were delivered with basic infrastructure (e.g. water and energy supply, services, bus stop), the surroundings do not have harmful impact fonts (e.g. highways, airports, dumping ground, industries), and improved them as well as recovered degraded sites. Making improvements in development surrounds is a way to increase the project sustainability, but for this, a wider urban context must be incorporated (Sharifi and Murayama, 2014). Though this category considers a broader context, integration and relationships between urban infrastructure and the project, it is only focused on environmental aspects.

In design & comfort, no project met the community interrelation criterion, which assess negatives impacts of development in neighbourhood. The combination of land limitation and pressing need for delivering numerous HUs prevented that all current neighbourhood conditions were respected. Paraisópolis also did not score in alternative transportation criteria, because topography does not allow using bicycles, and it does not

have private collective transportation, nor ventilation and daylighting in bathrooms. For Project Várzea, design detail was not sufficient yet to assess flexible design, daylighting in common areas and adaptation to local topography criteria. TOD application helped this project to meet the criterion for alternative transportation, but TOD addresses many other improvements than Casa Azul, i.e. existence of bikers, bike paths or collective private transportation. This category depends on local climatic conditions, i.e., strategies to achieve comfort vary according to Brazilian bioclimatic zone, what confers some adaptability to the tool. However, like verified in other research (Retzlaff, 2009), tool adaptability is restricted to this issue.

Regarding energy efficiency, it was not possible to assess solar heating system for Project Varzea, a criterion that Paraisópolis did not meet. This is the category with worst performance for Paraisópolis that did not comply with 'gas heating system', 'efficient elevators' (not applicable to that design), 'efficient appliances', and 'alternative energy sources' requirements. This strongly contrasts with most sustainability expectations, which normally have energy as the most valued criterion. Project Várzea did not comply with 'efficient elevators' and 'efficient appliances'. 'Material resources', 'modular design', 'industrialized or prefabricated components' and 'façades durability' could not be assessed for Project Várzea due to lack of information in the available documents. From the criteria assessed, 'optimized concrete mix', 'use of cement types CPIII and CP IV' and 'CDW pavement' were not met. Paraisópolis also did not score in the latter two criteria, besides 'usage of certified wood'. With some simple modifications in these items, the project would improve its score. For different reasons, none of the projects scored in elementary water management aspects. Project Várzea has not reached design detailing enough to allow assessment. Paraisópolis, however, did not score in rainwater harvesting and rainwater drainage, which is quite surprising. Given the considerable annual precipitation in the region, these are valid and usually feasible strategies solutions for saving water.

Paraisópolis scored best regarding social practices, meeting all of the criteria. For not have been built yet, Project Várzea could not be assessed employees' personal development and professional training, residents' environmental training, and capacity building for entrepreneurship management criteria. These social aspects do not incorporate adaptation, i.e. the differences between countless Brazilian regions and housing typologies that Casa Azul is applicable to. Though it considers some economic criteria, Casa Azul does not offer a broader assessment of costs relationship to deliver, own and maintain sustainable social housing. No residents participation was registered in development or feedback processes, despite being highlighted by previous research (Retzlaff, 2009; Sharifi and Murayama, 2013; Sullivan and Ward, 2012) as important to social and economic issues. Since several criteria could not be assessed, Project Várzea's score would range between 33 and 46, whilst Paraisópolis achieved 39 points. This difference is however irrelevant for certification purposes, and both projects would reach gold level, the maximum rating. Hence, Casa Azul seems to be unable to distinguish important conceptual and sizing differences.

Table 2. Selo Casa Azul assessment results for 'Paraisópolis' and 'Project Várzea'

Categories	Paraisópolis	Project Várzea
Urban Quality	4/5	4/5
Design & Comfort	8/11	7 to 10/11*
Energy Efficiency	3/8	5 to 6/8*

Material Resources	7/10	4 to 7/10*
Water Management	6/8	6 to 8/8*
Social Practices	11/11	7 to 11/11*
Overall score	39	33 – 46*
Level	Gold	Gold

\*Project's minimum and maximum scores, depending on performance results for criteria non-assessed here

In the HQI assessment, Project Várzea scores best for 'location', 'site' and 'external environment' (Table 3). Like in Casa Azul, aspects beyond project site are considered only in one indicator (location). For 'routes and movement', and 'external environment', scores were boosted by TOD application, which however did not change the Casa Azul award level. Simple design adaptations would increase the HQI score; however, at increased investment.

Table 3. HQI assessment results of 'Project Várzea'

Criteria	Score
Location	72%
Site	Visual Impact, Layout and Landscaping
	Open Space
	Routes and Movement
Unit	Size
	Layout
	Noise, Light, Services & Adaptability
	Accessibility within the unity
	Sustainability
External Environment - Building for Life	Environment and Community Character Streets, Parking and Pedestrianisation Design and construction
Overall score	47%

Worst scores are related to open spaces and unit aspects. In open spaces, the main cause of low score is the lack of children's playgrounds and the existence of open spaces without specific use. The last issue causes vulnerability to safety and security, once these areas can be intrusively used. For unit aspects, size of Brazilian social housing units is not consistent with the UK standards that ground HQI. Units in Project Várzea range from 42.90 m<sup>2</sup> to 47.65 m<sup>2</sup> for four bedspaces. In HQI, the minimum sizing for accommodating four residents is between 67 and 75 m<sup>2</sup>, so the examined project falls more than 10% short of its lowest limit, and has no extra room above the minimum required by the HQI standard. All spaces but bedrooms meet sizing requirements for furniture provision, access, circulation and activity zones, but none of them does so by exceeding the minimum requisite. Additional features related to suitable rooms to activities beyond usual are also weakly attempted. Regarding 'noise, light, services & adaptability', the project does not achieve any characteristics for noise reduction (which includes but is not limited to UK requirements), and have a weakly service provision, no additional features for services and no characteristics for adaption.

Finally, 'sustainability criteria' in HQI refer mainly to UK standards and regulations and do not allow for change or adaptation, following the standard of most sustainability assessment systems (Retzlaff, 2009, 2008; Sharifi and Murayama, 2013). The indicator is

divided in three parts - Code for Sustainable Homes, EcoHomes and Rehabilitation – from which one must be chosen. The first two parts refer to new projects and are exclusive to UK context. Rehabilitation is subdivided into energy, lighting, water and others sustainability aspects. Total score in sustainability indicator for Project Várzea results from this last part, to provide low-energy fittings in every room and solutions for good water management.

### Final Remarks

Casa Azul balances environmental and social issues but did not distinguish performance of very different assessed projects. Complete assessment is hampered at early project stages. On its turn, HQI focuses on environmental issues and is based on British standards and practices, which establish requirements that Brazilian social housing projects are not able or not expected to meet, such as unit sizes. Furthermore, despite admitting certain weighting adjustments, this adaptability is limited to the UK context.

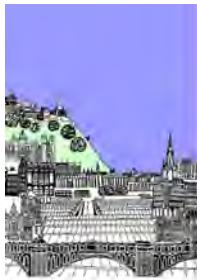
None of the systems consider a broader range of economic aspects or increased urban complexity at neighbourhood scale. Residents' participation is also unexplored. Our assessments confirmed that both tools have limitations and - if used in isolation – would not adequately describe fundamental sustainability aspects. A mixed or adapted set of indicators, encompassing housing unit, context and user character, from environmental, economic and social perspectives, is therefore needed to provide more meaningful results and design inputs, as well as serve as effective funding screening tools.

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### References

- Berardi, U., 2011. Beyond Sustainability Assessment Systems: Upgrading Topics by Enlarging The Scale of Assessment. *Int. J. Sustain. Build. Technol. Urban Dev.* 2, 276–282. doi:10.5390/SUSB.2011.2.4.276
- Gonçalves, J.C.S., 2016. Sustainability: a clarion call for a new approach. *Archit. Des.* 86. doi:10.1002/ad.2055
- Harrison, A., 1999. Housing Quality Indicators, in: Better Homes in the Next Millennium. Hong Kong Housing Authority, Hong Kong.
- ITDP, 2014. TOD Standard v2.1. Despacio, New York.
- John, V.M., Prado, R.T.A. (Eds.), 2010. Selo Casa Azul: Boas práticas para habitação mais sustentável. CAIXA, São Paulo.
- Retzlaff, R.C., 2009. Green buildings and building assessment systems: A new area of interest for planners. *J. Plan. Lit.* 24, 3–21. doi:10.1177/0885412209349589
- Retzlaff, R.C., 2008. Green building assessment systems: A framework and comparison for planners. *J. Am. Plann. Assoc.* 74, 505–519. doi:10.1080/01944360802380290
- Sharifi, A., Murayama, A., 2014. Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US, the UK, and Japan. *Build. Environ.* 72, 243–258. doi:10.1016/j.buildenv.2013.11.006
- Sharifi, A., Murayama, A., 2013. A critical review of seven selected neighborhood sustainability assessment tools. *Environ. Impact Assess. Rev.* 38, 73–87. doi:10.1016/j.eiar.2012.06.006
- Sullivan, E., Ward, P.M., 2012. Sustainable housing applications and policies for low-income self-build and housing rehab. *Habitat Int.* 36, 312–323. doi:10.1016/j.habitatint.2011.10.009
- The National Affordable Homes Agency, 2008. 721 Housing Quality Indicators (HQI) Form. Housing Corporation.



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*Design to Thrive*

## Meta-study of building fabric performance gap in low energy housing in UK

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**Abstract:** This paper presents findings from a national meta-study of the difference between designed and as built thermal performance of the building fabric of 188 (50 Passivhaus and 138 non-Passivhaus) low energy dwellings in the UK, which were evaluated as part a national Building Performance Evaluation Programme. The majority was social housing constructed with masonry and timber frames and equipped with MVHR systems. Design and measured data including airtightness, whole house heat loss and external wall/roof U-value was evaluated comparatively and assessed statistically along with the review of thermal imaging data. The findings revealed a prevalent performance gap rooted in thermal deficiencies occurring across the building fabric. The gap was more profound in terms of airtightness and smaller in regard to thermal transmittance and whole house heat loss. The extent of underperformance was minimal among Passivhaus structures and considerable among non-Passivhaus which presented an average gap of  $2\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$ . The results demonstrate the need to improve site workmanship and re-enforce the need for in-situ performance verification to bridge the gap between design intent and as built performance.

**Keywords:** Building fabric performance, low energy dwellings, Passivhaus, airtightness, space heating energy

### Introduction

Mounting evidence since the 1990's has firmly established that buildings, residential and commercial, often demonstrate a discrepancy between predicted and in-use energy consumption (Carbon Trust, 2011). The causes of the "performance gap" span throughout the building process and can be broadly classified into those relating to occupancy, energy performance of services and systems and the thermal performance of building fabric, which is the focus of this paper. Heat loss through the fabric is primarily the result of air leakage and of repeating and non-repeating thermal bridging. In a typical new build dwelling, thermal bridging can account for 20-30% of the total heat loss (Zero Carbon Hub, 2016) while the respective share of air leakage may be up to 50% (Energy Saving Trust, 2009). Underperforming fabric elements can therefore have significant impact on energy use and particularly on space heating which, accounting for over 60% of total energy, is by far the biggest slice of UK household energy use (DECC, 2013).

In response to the worldwide shift towards the use of building energy regulations and codes aimed at reducing energy consumption, there have been a number of studies on the evaluation of building fabric performance. Much of the work however has been case-study-focused and as a result findings have been largely fragmented. A study of 44 cavity masonry homes found a third of the pressure-tested properties underperforming, highlighting the impact of design complexity on the performance gap (Wingfield et al, 2008). Considerable discrepancies in the range of  $0.8\text{-}4.7\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$  were identified in 5 dwellings built to

EcoHomes Excellent and CSH 5&6 (Gupta et al, 2013), similarly to 6 CSH 4&5 dwellings where the actual airtightness was up to two times worse than design expectations (Gupta and Kapsali, 2015). Further representative of the air permeability gap in low energy housing were the discrepancies of  $6.2\text{-}8.6 \text{m}^3/\text{h}/\text{m}^2$  @ 50Pa in 6 timber dwellings built to CSH 4 which resulted in 50% higher heat loss (Bell et al, 2010). Failure to meet the design target has been also seen in Passivhaus dwellings, where however the gap is considerably smaller spanning up to  $0.7 \text{m}^3/\text{h}/\text{m}^2$  @ 50Pa (GHA, 2014 & Johnston et al, 2016).

Co-heating tests are currently the only established method of determining the thermal performance of a whole building envelope. The extent of publicly available data is not extensive, but the increasing number of such tests reflects the need to investigate post-construction performance. An evaluation of 3 dwellings built to EcoHomes Excellent and CSH 6 highlighted deviations from the SAP calculations in the range of 3-23% (Gupta et al, 2013), while a study of 25 dwellings built to Part L1A 2006 or better yielded 1.5 times higher HLC than predicted denoting an average gap of 50% (Johnston et al, 2015). A wide range of discrepancies has been reported in respect to CSH 4 dwellings; from 12-15% (Farmer et al, 2014) in two detached dwellings to 54% across 6 timber-framed homes (Bell et al, 2010) and even higher, 131-189% across 7 dwellings of different construction (AIMC4, 2014). Higher heat loss than calculated has been additionally identified in Passivhaus constructions, where the gap however is generally lower and of similar magnitude (6-21%) across the different studies (Guerra-Santin et al, 2013; Johnston et al, 2016; Johnston & Siddall, 2016).

The frequent inconsistency between design and in-situ thermal transmittance provide further evidence for the building fabric performance gap. The large-scale study at Stamford Brook is a representative example where the effective U-value was twice the design U-value of the external wall and nearly three times that of the floor and ceiling (Wingfield et al, 2008). Another study of 25 dwellings found the whole building U value over 1.6 times higher than the steady state predicted value (Johnston et al, 2015). Deviations from the design targets have been seen in Passivhaus dwellings as well, however similarly to airtightness and heat loss, the gap appears to be much lower and often negligible; U-value measurements of external walls and roofs have revealed discrepancies in the range of  $0.01\text{-}0.06 \text{ W/m}^2\text{K}$  and  $0.05\text{-}0.06 \text{ W/m}^2\text{K}$  respectively (Guerra-Santin et al, 2013; GHA, 2014; Johnston et al, 2016).

The performance of building fabric is largely determined by design and construction. Aiming towards a comprehensive understanding of the fabric performance gap in low energy housing and its effect on actual space heating energy, this study uses the meta-study approach to evaluate with increased statistical power the difference between design and as build air permeability, thermal transmittance and whole house heat loss of dwellings from comparable studies, thus allowing for conclusions applicable to the wider new build housing population.

### **Overview of the study: data sources and methods**

The study comprises an extensive review and analysis of the “as designed” and “as built” fabric thermal performance data generated in 53 studies of new build and low energy dwellings in the UK, in the course of the £8 million Building Performance Evaluation programme (2010-2014) funded by Innovate UK (Innovate UK, 2014). The dwellings were located across 44 developments in N. Ireland (1 out of 44), Wales (2 out of 44), Scotland (9 out of 44) and predominantly England (32 out 44), and were occupied during the “in-use” phase of the studies. The fabric performance had been investigated using diagnostic field tests including an air-permeability test, whole house heat loss test, heat flux measurements

and infrared thermal imaging surveys. Using a range of data sources such as the studies' final report, SAP and DomEarm spreadsheets the study developed a large database of air permeability, whole house heat loss, external wall and roof U-values and thermal imaging data. The database comprises 138 non-Passivhaus (NPH) and 50 Passivhaus (PH) including 94 houses, 89 flats and 5 bungalows with floor areas from 37m<sup>2</sup> to 346m<sup>2</sup>, designed to diverse standards from Passivhaus and Fabric First approach to Code of Sustainable Homes (CSH 2-6) and Building Regulations. The construction types included structural insulated panels (SIPs), steel, concrete and predominantly the traditional masonry (73 out of 188) and timber frames (80 out of 188). In terms of ventilation strategy, passive systems for natural ventilation (NV) and mechanical extract ventilation (MEV) were adopted in 10% and 5% of the dwellings respectively, whereas the overwhelming majority (85%) used Mechanical Ventilation with Heat Recovery (MVHR). The most common tenure type was social housing (133 out of 188). Figure 1 illustrates the percentage distribution of these characteristics separately for the PH and NPH dwellings.

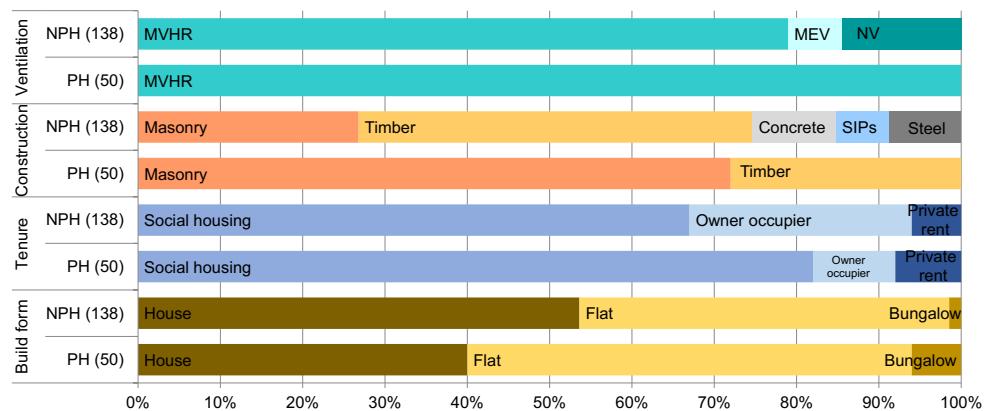


Figure 1: Build form, tenure type, construction system and ventilation strategy for the 188 dwellings reviewed, separately for Passivhaus (PH) and non-Passivhaus (NPH) dwellings.

Data was analysed by means of the Statistical Package for Social Sciences (SPSS). A statistical analysis plan was developed to maximise uniformity in data analysis and ensure validity of results. Thermal imaging data was analysed at the development level while air permeability, heat loss and U-value data at dwelling level with the respective sample sizes varying between 188 for air permeability and 29 for heat loss due to data availability (Table 1).

Table 1: Sample size of dwellings (and developments for thermal imaging) reviewed.

	Air permeability	External wall U-value	Roof U-value	Whole house heat loss	Thermal imaging
Passivhaus	50	14	5	6	10
Non-Passivhaus	138	48	15	23	34
Total	188	62	20	29	44

## Results

### **Designed and measured airtightness**

Design and in-situ data were reviewed for 188 dwellings in 43 developments. The measured data originated from air permeability tests conducted to the ATTMA standard (ATTMA, 2010), though the test had been extended to include both pressurisation and depressurisation with the final air permeability result represented by the average of the two. The average measured air permeability over the 188 dwellings (3.8m<sup>3</sup>/h/m<sup>2</sup>@50Pa) was

marginally lower than the average design target ( $4.0\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$ ), however the median design and measured values were 3.0 and  $4.0\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$  respectively denoting a performance gap. This was validated from the weak statistical relationship between design and measured air permeability for PH and no relationship for NPH (Figure 2a) as well as from the large number of dwellings (96 out of 188; 51%) that failed to meet design air permeability (Figure 3). This was the case with over half the PH dwellings (29 out of 50; 58%) and nearly half the NPH dwellings (67 out of 138; 49%) which presented an average gap of 0.5 and  $1.9\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$  respectively.

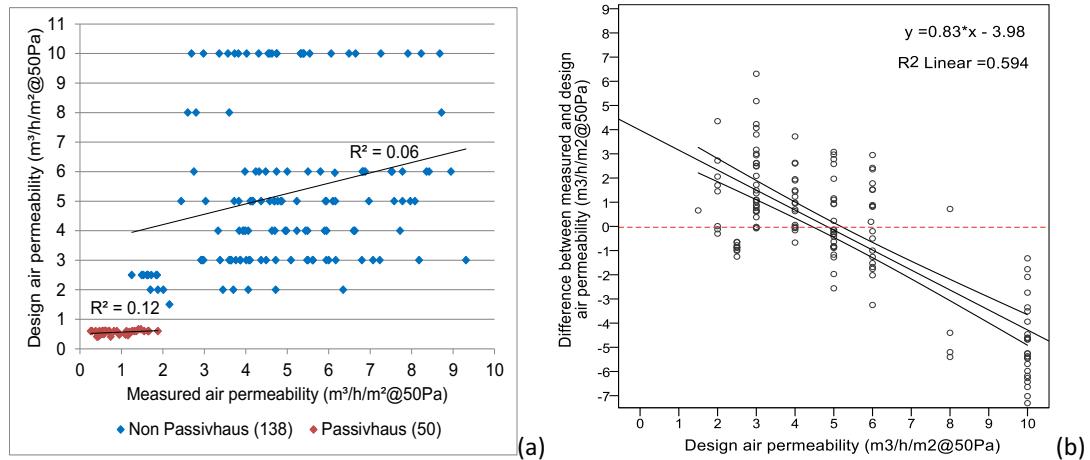


Figure 2: (a) Relationship between design and measured air permeability, (b) rate of change of the difference between measured and design air permeability with changes in the design target for 138 NPH dwellings.

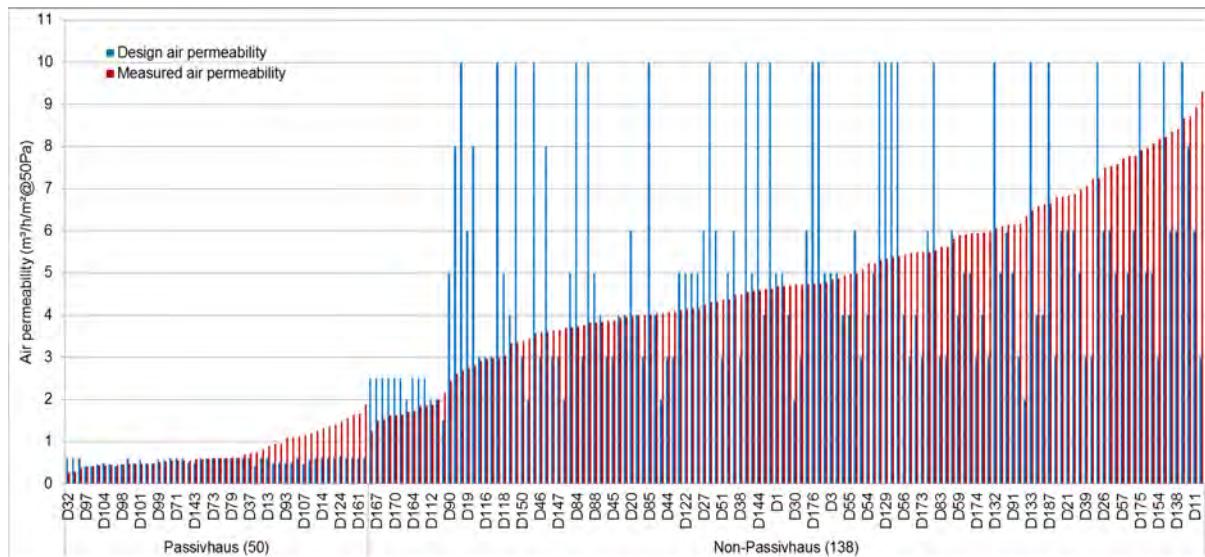


Figure 3: Design and measured air permeability for 50 Passivhaus and 138 non-Passivhaus dwellings.

Further scrutiny of the airtightness data revealed a strong tendency of NPH envelopes designed to  $5\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$  or better to demonstrate an air permeability gap. The regression model in figure 2b (significant at  $p<0.05$ ) shows that the lower the design air permeability, the difference between measured and design air permeability increases, indicating the importance of workmanship in achieving high levels of airtightness. The model implies that for every  $1\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$  decrease in design air permeability the gap between actual and intended airtightness increases by  $0.8\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$ , with the cut-off point at  $5\text{m}^3/\text{h}/\text{m}^2@50\text{Pa}$ .

### **Thermal transmittance of building elements and whole-house heat loss**

In-situ external wall U-value (measured in accordance to ISO 9869; ISO, 1994) was compared against the design intention for 14 PH and 48 NPH dwellings in 37 developments. The mean measured U-value was higher than designed by only 0.03 W/m<sup>2</sup>K (+27%) in PH dwellings and by 0.07 W/m<sup>2</sup>K (+39%) among NPH dwellings. The intended performance was not achieved in 8 out of 14 PH and 29 out of 48 NPH, denoting an average gap of 0.05 W/m<sup>2</sup>K and 0.14 W/m<sup>2</sup>K respectively, while in 12 cases the measured U-value exceeded the Part L1A limit.

Roof U-value data was reviewed for 5 PH and 15 NPH dwellings in 14 developments. Similarly to external walls, the mean measured roof U-value was marginally higher than designed in both PH and NPH dwellings, by 0.04 W/m<sup>2</sup>K (+44%) and 0.10 W/m<sup>2</sup>K (+71%), and the gap among the underperforming dwellings was higher among NPH. The roof element had failed to perform to its design intention in 4 out of 5 PH and 11 out of 15 NPH presenting an average discrepancy of 0.04 W/m<sup>2</sup>K and 0.15 W/m<sup>2</sup>K respectively.

The investigation of whole house heat loss involved data from 6 PH and 23 NPH buildings in 21 developments. The co-heating tests had been undertaken in accordance to the Leeds Becket University protocol (Wingfield et al, 2010) though in certain cases deviations were necessary. The majority of dwellings - 5 out of 6 PH and 15 out of 23 NPH - was seen to underperform demonstrating an average gap of 4.5 W/K and 42.1 W/K respectively. The percentage deviation across the total sample of PH dwellings was only 5% but significantly higher at 20% among NPH dwellings, regularly exceeding the generally accepted close match between predicted and measured HLC of 10-15% (Bell et al, 2010).

### **Link between fabric performance and measured space heating energy use**

Measured air permeability and HLC data was analysed against measured heating energy data to investigate the impact of fabric thermal performance on space heating. The results indicated an overall very weak relationship ( $R^2=0.18$ ) with air permeability (Figure 4a), which is inexistent for NPH dwellings ( $R^2=0.07$ ) and moderate for PH dwellings ( $R^2=0.65$ ), demonstrating that high levels of airtightness do not guarantee low heating energy as other factors such as type of heating system, controls, and occupant behaviour are also important contributors. Interestingly, a very strong relationship was found between space heating energy and HLC (Figure 4b), implying that a comprehensive building fabric test may be more reliable than just an air permeability test currently required in the Building Regulations.

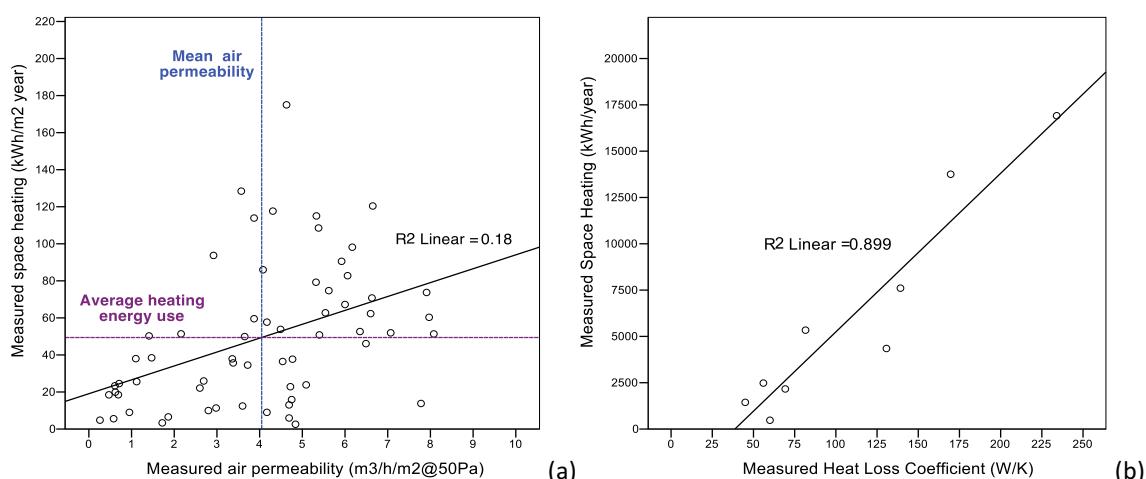


Figure 4: Relationship between space heating and (a) air permeability for 188 dwellings and (b) heat loss coefficient for 9 non-Passivhaus dwellings.

### ***Identifying likely thermal defects using thermal imaging survey data***

A review of the qualitative data gathered through internal and external thermal imaging surveys in the 44 developments was undertaken to identify the breadth and frequency of fabric locations with thermal deficiencies. The results highlighted openings as the weakest fabric element; heat loss and air leakage through windows and doors were identified in the vast majority (84%) of developments (Table 2). Common areas of weakness, as pinpointed in nearly half the developments, were also the junctions and joints as well as the roof at the eaves level and loft space with common causes the inadequate insulation and/or poor packing of insulation into the eaves and heat loss from the loft hatch and interface with the ceiling. In a smaller, yet considerable fraction of sites (25%), localised thermal bridging was found in walls (34%) and ceilings (25%) as well as in service penetrations and fittings (23%) such as MVHR supply vents and extract fans. Other defects with similar frequency of occurrence include air leakage through boxed-in sections and unregulated heat gain from insufficiently insulated heating manifold cupboards, heating and hot water pipework, overall indicating that thermal deficiencies can occur anywhere within the building fabric.

Table 2: Faulty areas and frequency as revealed from thermal imaging surveys in 44 developments.

	Roof/Eaves & loft space	Junctions & Joints	Walls only	Ceilings only	Windows & Doors	Fittings/Service penetrations	Slab/ground level	Other
Overall (44 developments)	20/44	21/44	15/44	11/44	37/44	10/44	4/44	11/44
Passivhaus (10 developments)	2/10	0/10	3/10	3/10	10/10	1/10	0/10	2/10
Non-Passivhaus (34 developments)	18/34	21/34	12/34	8/34	27/34	9/34	4/34	9/34

A comparison between the NPH (34) and PH (10) developments revealed a significantly lower frequency of defects among the latter, thus highlighting the importance of attention to detail. Defects associated with the roof, eaves and loft space for instance, were revealed in only 2 out of 10 PH developments and in over half (18 out of 34) NPH developments. Moreover, thermal deficiencies in junctions and joints were found in over 60% (21 out of 34) of the NPH developments and in none of the PH developments (Table 2).

### **Discussion**

The analysis of fabric thermal performance data from 188 new build homes revealed widespread deviations from the design intent in the majority of dwellings. The greatest discrepancies were seen in airtightness whereas the gap in terms of whole house heat loss and thermal transmittance of roof and external wall was smaller. With nearly all developments presenting deficiencies at windows and doors, thermal weakness at openings seems to be endemic across the sector (Table 2). The review of thermographic data however indicated that thermal defects can occur anywhere within the building fabric, from junctions/joints and roofs to slab/ground level and service penetrations, thus highlighting the need to improve detailing, specification and workmanship. The prevalence of the fabric performance gap amongst this sample of dwellings designed and constructed to low energy standards by expert teams who were aware of the monitoring and testing commitment, indicates a widespread occurrence of this gap across the UK new build housing population.

PH dwellings require meticulous attention to detail to achieve the high airtightness levels required for certification. Although the fraction of underperforming dwellings was higher among PH builds, the deviation from the design intent was most often insignificant and within expectations. On the contrary, the gap was consistently higher among NPH dwellings across the entire spectrum of fabric performance including airtightness, thermal transmittance and whole house heat loss, thus highlighting the design and attention to detail as key differentiating factors between the performance gap in PH and NPH dwellings.

While airtightness is a key determinant of space heating, the weak relationship between actual air permeability and heating energy use (Figure 4a) indicates the influence of other factors, denoting that designing and building airtight homes does not necessarily lower space heating energy use. This also suggests that a holistic approach to building monitoring is necessary that includes services, systems and measurement of occupant behaviour. The strong relationship between space heating energy use and HLC (Figure 4b) shows that a comprehensive fabric test would be more reliable than air permeability test as currently required. The prevalence and extent of the fabric underperformance, such as the air permeability gap of  $1.9\text{m}^3/\text{h}/\text{m}^2$  @ 50Pa among NPH dwellings, also raises the need to have accurate and updated as-built energy models that are based on measured data and capture the impact of design or construction changes on energy use.

## Conclusions

This research has undertaken a meta-study of the building fabric thermal performance gap in 188 low energy dwellings in the UK, including Passivhaus (50) and non-Passivhaus structures (138), drawn from the Government's Building Performance Evaluation Programme. Actual air permeability, whole house heat loss and thermal transmittance of external wall and roof, determined from in-situ measurements, were compared against the design intention and reviewed along with thermographic survey data. The findings show that building to the design intent is not commonplace. The prevalence of the fabric performance gap, more profound in terms of airtightness, and the occurrence of thermal defects across the building fabric has raised the need for better construction quality and diagnostics. A comprehensive fabric test including air permeability, heat flux measurements and thermal imaging in all dwellings can be more reliable than just an air permeability test in a sample of dwellings as currently required in Building Regulations and can inform as build energy models to produce predictions closer to actual performance. Ultimately, identifying the underlying causes of the fabric performance gap is important to a range of key stakeholders including designers, M&E consultants, constructors and policy-makers. Such knowledge should inform the future versions of Building Regulations, which can require more in-situ testing of the building fabric during the construction and completion stages.

## Acknowledgements

We are grateful to Innovate UK for sponsoring the I-life research project.

## References

- AIMC4 (2014). *Information paper - Lessons from AIMC4 for cost-effective fabric-first low-energy housing Part 5: As-Built performance and Post Occupancy Evaluation*. AIMC4 consortium, June 2014.
- ATTMA (2010). *Technical Standard L1: Measuring Air Permeability of Building Envelopes (dwellings)*.
- Bell, M., Wingfield, J., Miles-Shenton, F., Seavers, J. (2010). *Low carbon housing: Lessons from Elm Tree Mews*. York: Joseph Rowntree Foundation.

- Carbon Trust (2011). *Closing the Gap: Lessons Learned on Realising the Potential of Low Carbon Building Design*. Report CTG047, London, 2011.
- DECC (2013). *United Kingdom Housing Energy Fact File 2013*. Department of Energy and Climate Change.
- Energy Saving Trust (2009). *Enhanced Construction Details: Thermal bridging and airtightness*. CE302.
- Farmer, D. Johnston, D. Sutton, R. Stafford, A. Eaton, C. (2014). *GHA Monitoring programme 2011-2013: Technical report (Derwenthorpe prototypes)*. Good Homes Alliance, London.
- GHA (2014). *Community in a Cube: Riverside One case study*. Good Homes Alliance, London.
- Guerra-Santin, O. Tweed, C. Jenkins, H. Jiang, S. (2013). Monitoring the performance of low energy dwellings: Two UK case studies. *Energy and Buildings*, 64, 32-40.
- Gupta, R. Gregg, M. Cherian, R. (2013). *Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing*. ECEEE 2013 Summer Study proceedings.
- Gupta, R. Kapsali, M. (2015). Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK. *Advances in Building Energy Research* 2015.
- Innovate UK (2014). *Building Performance Evaluation: Overview of the Programme Portfolio*. November 2014.
- ISO (1994). *Thermal Insulation - Building Elements - In-Situ Measurement of Thermal Resistance and Thermal Transmittance*, ISO 9869: 1994.
- Johnston, D. Farmer, D. Brooke-Peat, M. Miles-Shenton, D. (2016). Bridging the domestic building fabric performance gap. *Building Research & Information*, 44(2), 147-159.
- Johnston, D. Miles-Shenton, D. Farmer, D. (2015). Quantifying the domestic building fabric 'performance gap'. *Building Services Engineering Research and Technology*, 36(5), 614-627.
- Johnston, D. Siddall, M. (2016). The building fabric thermal performance of Passivhaus dwellings - does it do what it says on the tin? *Sustainability*, 8(1), 97.
- Wingfield, J. Bell, M. Miles-Shenton, D. Lowe, B. South, T. (2008). *Partners in Innovation project. Lessons from Stamford Brook - Understanding the Gap between designed and real performance*, Report Number 8 - Final Report, November 2008.
- Wingfield, J. Johnston, D. Miles-Shenton, D. Bell, M. (2010). *Whole House Heat Loss Test Method, (Coheating)*. Centre for the Built Environment, Leeds Becket University, May 2010.
- Zero Carbon Hub (2016). *Thermal Bridging Guide - An introduction to thermal bridging in homes*. London, February 2016.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Buiksloterham Integrated Energy Systems

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**Abstract:** The traditional way of supplying energy to the built environment is no longer suitable: New buildings with high energy performance and decentralised renewable energy generation, together with the desire to become fossil-free, involve the need for new, more flexible and more integrated energy systems. The district of Buiksloterham was a test case to develop feasible and potentially desirable energy supply scenarios for the built environment at district level. It is not possible to develop Buiksloterham, and similar areas with high density, into an energy neutral area within the current legal framework (without wind energy it is not possible). About 1/3 of the energy use in buildings (building-related and user-related) can be supplied by renewable energy. In Buiksloterham a low temperature supply of heat is essential for a maximised use of renewable input. A fourth, low temperature, energy concept, consisting of local heat generation from solar and waste, thermal storage, and heat pumps, seems the best integrated energy system. The non-technical lesson learned is that new energy-efficient energy systems require very good, early planning, appointments, and cost and support of existing energy suppliers. Extracting a CO<sub>2</sub> neutral society by 2050 also depends on implementation aspects i.e. not only CO<sub>2</sub> and costs but also circularity parameters such as the use of resources for equipment, water, biodiversity, health, adaptability and resilience must be considered.

**Keywords:** Energy, Systems, District

### Introduction

The traditional way of supplying energy to the built environment is no longer sustainable: New buildings with high energy performance and decentralised renewable energy generation, together with the desire to become fossil-free, need new, more flexible and more integrated energy systems. The city of Amsterdam has a large programme for new buildings (Gemeente Amsterdam). At the same time, the city's ambition is to become independent of natural gas for energy supply to the built environment by 2050. New buildings, therefore, should not be connected to the gas grid anymore.

Innovative scenarios for a flexible and integrated energy system are developed within the Buiksloterham Integrated Energy Systems (BIES) project for the suburb of Buiksloterham located in Amsterdam-North, see figure 1. The results of this study should also be applicable to other new construction sites with high energy ambitions and high densities. Both technical and organisational boundary conditions are considered in this research.

The Buiksloterham area is located on the North side of the IJ-river relative to Amsterdam Central Station and can be reached within five minutes from the Central Station

with a free ferry service. The construction of the new “North-South” metro line, which will link the historic centre of Amsterdam with the northern side of the river, is scheduled for completion in early 2016 and will provide an important means of additional access. Buiksloterham, a former industrial area, is one of the larger new housing estates (around 100 ha) where 3500 new dwellings and around 200.000 m<sup>2</sup> working space is planned within the next 10 years.



Figure 1. The area of Buiksloterham (source: Bestemmingsplan Buiksloterham 2009)

## Literature

The starting point for the development of the technical energy concepts was the energy potential mapping approach by Dobbelsteen et al. (2007) and Broersma et al. (2013). The ‘toolkit duurzame gebiedsontwikkeling 2012’ and the report by Jablonska et al. (2011) were used for the development of both new energy concepts and new energy approaches.

However, the ambitions of the BIES project went beyond matching the energy potential to the demand. The wish of the district of Buiksloterham is to become a leading example of Circular City development in Amsterdam (Circular Buiksloterham report). This enforced the development of an integrated energy system that was sustainable in all its aspects. The district of Buiksloterham as a living lab required that the economic feasibility had to be taken into account to assure an affordable integrated energy system in the near future. And last but not least, to realise an integrated energy system in Buiksloterham is impossible if the political, social, technological, legal, and governmental aspects of the PESTLEG analysis are not considered.

The detailed quantitative analysis of the energy concepts and their evaluation on all the aspects mentioned above required an enormous amount of background literature. The energy demand of the buildings is based on the Dutch RVO (2015). An overview of all the other applied literature can be found in the final report of the project (Jansen et. al, 2016, in Dutch) as the page limit of this paper it too restricted to cite them all. Apart from the literature, a lot of information was also gained from stakeholders active in the area.

## Methods

For the development of the energy concept an integral approach was developed where circularity in all its aspects was taken into account as well as the political, economic, social, technological, legal and governmental aspects. The approach consisted of two routes that were followed simultaneously. The first route is the theoretical development of the basic energy concepts. The second route is the practical approach where stakeholder meetings

were used, as well as meetings with potential suppliers from industry, in order to improve the basic energy concept.

The area consists of existing and new buildings. Given the diverse nature of the existing buildings, the main focus was the energy concept for the new buildings. Recommendations for the existing buildings and the integration between the two are proposed in the project but not described in this paper.

### **Development of the Basic Energy Concept**

An inventory was made of the existing buildings and the plans for the new buildings. Use was made of the “bestemmingsplan” (land us plan set up under the authority of the municipality) and the existing report about the circular ambition of Buiksloterham (Metabolic and Delva Landscape Architects, 2014). The inventory also included an inventory of stakeholders and existing energy infrastructures.

The energy concepts were assed using Key Performance Indicators (KPI’s). These KPI’s are developed within the following categories: energy, economy, circularity and implementation. The implementation category, in turn, consists of the PSTLG indicators: Political, Social, Technological, Legal and Governance. The main KPI’s for energy are: the fraction of local renewable energy and the amount of CO<sub>2</sub> with the subcategories: energy use of existing buildings, energy use of new buildings and renewable energy potential, see the annual energy flow scheme in figure 2. The energy use data of existing buildings was obtained from [www.energieinbeeld.nl](http://www.energieinbeeld.nl). The energy potential on-site was estimated based on average roof surfaces for solar and average production of waste and waste water.

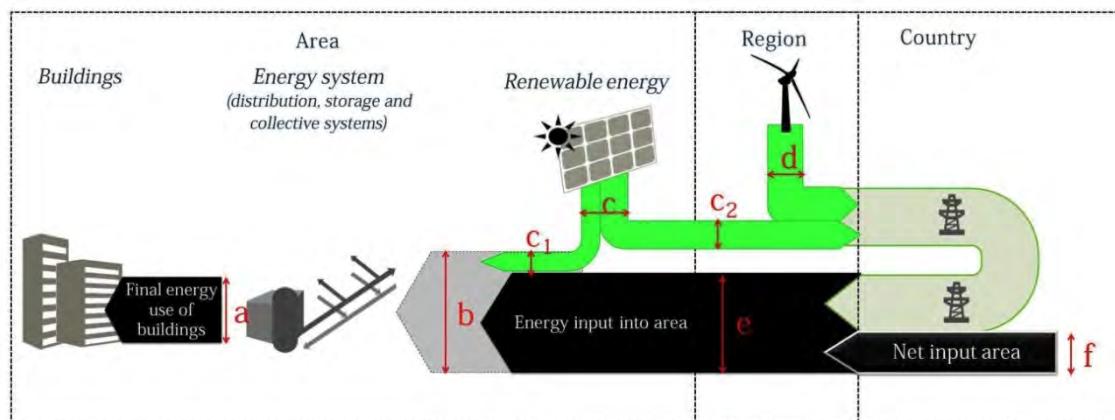


Figure 2. Schematic illustration of the Energy performance indicators in GJ/y (Jansen et al. 2015)

Two options were used as the starting point for the energy demand of new buildings. The first option has an energy efficient building skin, i.e. the Energy Performance Coefficient (EPC) of 0.4 of the building is reached with a standard energy system (HR gas boiler, electricity from the grid) and no sustainable production. In the other option, the insulation values of the building skin comply with the minimum values of the Dutch Building Regulations so that the EPC of 0.4 can be reached with efficient/sustainable energy solutions. The demand data for heating, cooling, domestic hot water and electricity consumption of the new buildings were based on reference numbers from RVO, 2015.

Three basic energy concepts for energy supply for the new buildings were developed based on proven and existing technologies: 1. Gas and electricity, 2. All-electric (heat pump and ground source thermal storage) and 3. District heating with electricity. Experience in the area and existing agreements between stakeholders were also taken into account in the

development of these energy concepts. The efficiencies of the technologies involved were taken from RVO, 2015 and from the experiences of the project partners.

### ***Development of the Energy Concept Advice***

In February 2016, a first stakeholder meeting with around 25 people active in the area was organised to discuss the basic energy concepts. The discussions revealed that more attention had to be paid to the specific local situation in Buiksloterham. The evaluation of the basic variants generated ideas for improvements for the new and existing buildings. In May 2016, a second stakeholder meeting was organised where improvement ideas were presented and further developed. Finally, the basic energy concepts were evaluated and ideas for further improvements were created. Several literature sources and stakeholders were additionally consulted to obtain the most correct data.

## **Results**

### ***Energy demand***

The total energy demand for heating and cooling for new buildings is between 40,000 and 50,000 GJ/year for heating (room heating and domestic hot water) and between 11,000 and 14,000 GJ/year for cooling, see figure 3. The electricity demand between 42,000 and 48,000 GJ/year is the sum of building related electricity (mainly lighting and ventilators) and user related electricity (computers, TV, etc.). The total energy demand for the existing buildings is the actual energy use in 2014 (data from the utility company Alliander), see table 1.

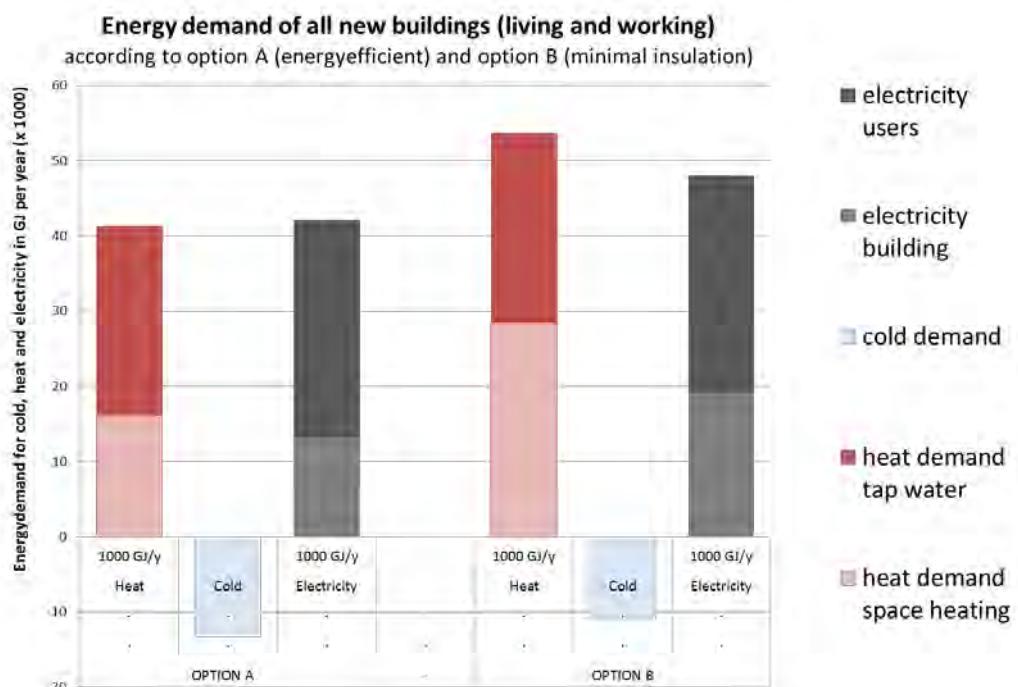


Figure 3: Total energy demand of the new buildings of Buiksloterham till 2024 for space heating, cooling and tap water. Option A and B represent different grades of insulation (A is very energy efficient and B according to the minimal values of the Dutch Building Regulations).

Table 1. Total energy use existing buildings (2014 data from utility company Alliander).

	Electricity usage existing buildings	Gas usage existing buildings
usual units	$27.0 \times 10^6$ kWh/year	$2.47 \times 10^6$ m <sup>3</sup> /year
GJ/year	$97.4 \times 10^3$ GJ/year	$86.7 \times 10^3$ GJ/year

## Energy potentials

The energy potential of the new buildings is shown in figure 4. The production of solar energy, electricity as well as heat, is considerable as the ambitious assumption is made that almost the entire roof area of the new buildings can be used for PV. PV on the facade is not taken into account.

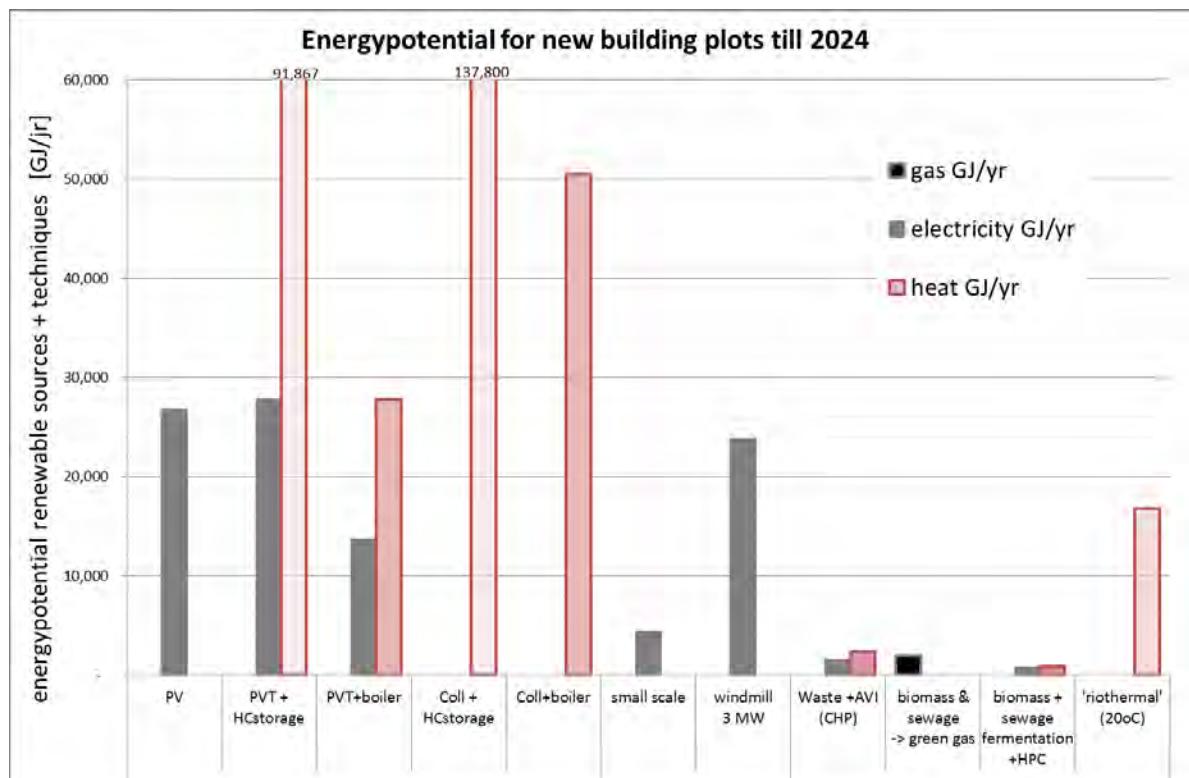


Figure 4. Energy potentials of new buildings from sun and wind on roofs and from waste and sewage.

The availability of local heat at relatively low temperatures (15 to 35 °C) is large. The PVT panels and solar collectors can produce more heat when the heat can be delivered at lower temperatures, for example combined with heat and cold storage in the ground instead of a boiler tank. Heat recovery from the sewage system, also called 'rio-thermal' energy, is another source of low temperature heat. Rio-thermal heat recovery has the advantage that this heat is also available in winter when there is less sun from the solar systems. A heat pump is, however, always necessary to upgrade the low temperature heat for room heating or domestic hot water. Attention should be paid to the fact that the necessary electricity for the heat pump is lower when the source temperature is closer to the supply temperature, even if the necessary amount of heat is the same.

The energy potential for waste is calculated assuming maximum reuse of recyclable elements. This means a high amount of organic waste and a low amount of refuse remaining after separation of recyclable elements. The remaining refuse after separation of recyclable elements can produce electricity and heat in a waste incineration plant and the organic waste can produce electricity and heat in a heat and power plant (after fermentation). Compared to the energy demand, only a very limited amount of biogas can be produced from the available waste and black water in the area.

Table 2. Overview of the assessment of the different energy supply concepts for new buildings

	Criterium	Concept 1	Concept 2	Concept 3
<b>1 ENERGY</b>				
	% local renewable	38%	55%	36%
	% Total (local + regional) renewable	54%	100%	49%
	CO2 emission [ton CO <sub>2</sub> /y]	2.443	-	787
	Selfsufficiency	Entire heat demand not self-sufficient	Local heat covered electricity not yet	Entire heat demand not self-sufficient
<b>2 ECONOMY</b>				
Costs Enduser		TOTAL € 12.919,-	TOTAL € 17.482,-	TOTAL € 20.522,-
Societal costs (use of existing infrastructure and need for new infrastructure)	Infrastructure gas	neutral	average	average
	Infrastructure electricity & peak power(MWp)	average (7,65)	average (7,65)	average (7,65)
	Infrastructure district heating	neutral	neutral	average
<b>3 CIRCULARITY</b>				
	Use of natural resources	circularity not possible	some bottlenecks	many bottlenecks
	Water	many bottlenecks	some bottlenecks	many bottlenecks
	Energy cumulative	some bottlenecks	many bottlenecks	many bottlenecks
	Biodiv. & Ecosystems	many bottlenecks	some bottlenecks	many bottlenecks
	Health & wellbeing	many bottlenecks	some bottlenecks	some bottlenecks
	Adaptivity & resilience	circularity not possible	no bottlenecks	many bottlenecks
<b>4 IMPLEMENTATION (PSTLG)</b>				
	Political	not possible	not possible	is promoted
	Social implications	bottlenecks	neutral	bottlenecks
	Technological	neutral	neutral	neutral
	Legal	not possible	bottlenecks	is promoted
	Governance	neutral	bottlenecks	neutral

### Energy concept assessment

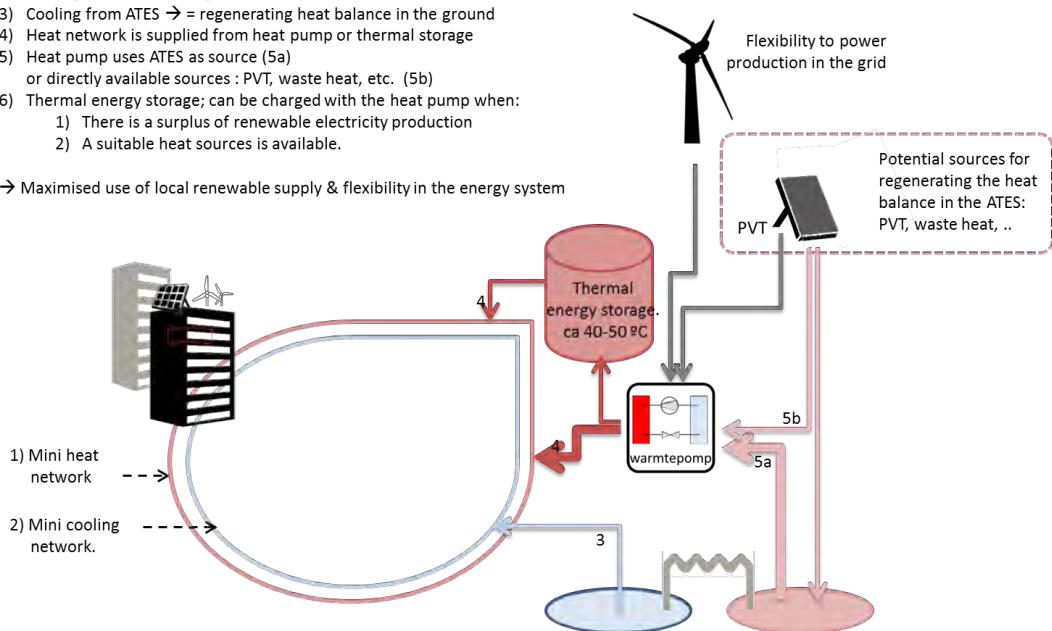
Table 2 shows the assessment of the energy concepts for the new dwellings. The assessment shows that concept 1 is by far the most favourable in terms of costs, followed by concept 2, and then 3. Concept 2 is the most favourable related to energy performance and overall sustainability. Given the existing agreements in Buiksloterham only concept 3 is applicable. The assessment also shows that none of the basic concepts is truly an integrated

energy system, where synergies are sought and flexibility for the grid is achieved. For example, the expected large quantity of installed PV power may even lead to an upgrade of the power grid.

To eliminate these shortcomings, a fourth variant was developed, based on maximum use of local heat, use of a collective heat pump and a mini heat network at low temperatures, around 40 °C, see figure 5. Storage of thermal energy is an essential part here, since in this way more local heat can be exploited and flexibility in the network is increased due to the flexible use of the heat pump. The ideal temperature and scale for such a collective energy concept and mini heat network remains to be investigated.

From the assessment of this fourth, alternative concept, it appears that the integrated approach can lead to more benefits than the basic concepts. The combination of more local heat produced with large (seasonal) thermal energy storage can increase the use of local renewable heat and increase the flexibility for the electricity grid. Collective systems can also have a higher efficiency, especially when thermal storage is involved. However, the problem with this kind of development is mainly the governance; only few parties can make large investments and exploit such systems. In Buiksloterham this proves especially difficult due to the different timing of different developments.

- 1) Space heating and domestic hot water with mini heat network
  - 2) Cooling with mini cooling network
  - 3) Cooling from ATES → = regenerating heat balance in the ground
  - 4) Heat network is supplied from heat pump or thermal storage
  - 5) Heat pump uses ATES as source (5a)  
or directly available sources : PVT, waste heat, etc. (5b)
  - 6) Thermal energy storage; can be charged with the heat pump when:
    - 1) There is a surplus of renewable electricity production
    - 2) A suitable heat source is available.
- Maximised use of local renewable supply & flexibility in the energy system



*Figure 5. Scheme of a fourth energy concept for the new buildings developed to overcome the shortcomings of the basic variants 1, 2, and 3.*

## Conclusion

It is not possible to develop Buiksloterham, and similar areas with high density, into an energy neutral area within the current legal framework (without wind energy it is not possible). About 1/3 of the energy use in buildings (building-related energy plus user-related energy) can be supplied by renewable energy. It is possible to identify which concepts result in the highest fraction of renewable supply: The BIES project concludes that a low temperature supply of heat is essential for a maximised use of local renewable input. The fourth energy concept developed seems to meet the ambitions related to maximum

renewable supply and system integration. This concept is based on local heat generation, thermal storage at relatively low temperatures, produced from solar energy or by upgrading low temperature (waste) heat by means heat pumps.

What can be learned from this project, besides the technical conclusions, is that new energy-efficient energy systems require very good, early planning, appointments, and cost and support of existing energy suppliers. Achieving a CO<sub>2</sub> neutral society by 2050 depends not only on technological innovation; implementation aspects have a significant impact. In the assessment of the most future proof and sustainable energy system an integrated approach is needed, that is: not only looking at CO<sub>2</sub> and costs but also including circularity parameters such as the use of resources for equipment, water, biodiversity, health, adaptability and resilience.

## References

- Bestemmingsplan Buiksloterham: [www.amsterdam.nl/projecten/buiksloterham/stedenbouwkundige](http://www.amsterdam.nl/projecten/buiksloterham/stedenbouwkundige), retrieved October 2017, *in Dutch*.
- Broersma, S. Fremouw M and Dobbelenstein A.van den., *Energy Potential Mapping: Visualising Energy Characteristics for the Exergetic Optimisation of the Built Environment*, Entropy 2013, 15, 490-506; doi:10.3390/e15020490.
- BUIKSLOTERHAM INTEGRATED ENERGY SYSTEM: Naar een duurzaam en geïntegreerd energiesysteem voor een wijk in transitie*, November 2016, *in Dutch*.
- Dobbelenstein, A. A. J. F. vd., Jansen, S. C. and Timmeren, A. v. (2007). "Naar een energiegestuurd omgevingsplan Groningen" (In Dutch). Delft, Delft University of Technology, *in Dutch*.
- Gemeente Amsterdam, Koers 2025: <https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/koers-2025-amsterdam/>, rectrived 17/3/2017, *in Dutch*.
- Jablonska,B. et al., *Innovatieve energieconcepten en pilots voor energieneutrale gebiedsontwikkeling in 2050*, ECN-0-10-037, January 2011, *in Dutch*
- Jansen, S.C., Bokel, R.M.J., Müller, S., Elswijk, M., Roossien, B., Odijk, S. van., Vries, S. de, *BIES* (2016). <http://www.ams-institute.org/solution/bies-buiksloterham-integrated-energy-system/>, *in Dutch*.
- Kleerekoper, L., Taleghani, M. , Dobbelenstein van der A.A.J.F., Hordijk, G.J. *Urban Measures for hot weather conditions in a temperate climate condition: a review study*, Renewable and Sustainable Energy Reviews 2017, 75, 515-533.
- Metabolic, Studioninedots & DELVA Landscape Architects, *Circulair Buiksloterham. Een Living Lab voor circulaire gebiedsontwikkeling*, Creative Commons licentie (CC-BY-NC-ND 2014), *in Dutch*.
- RVO, *Uniforme maatlat gebouwde omgeving, rekenmodel versie 3.5*. Online download from [www.agentschapnl.nl/new](http://www.agentschapnl.nl/new) --> instrumenten. Retrieved October 2015, *in Dutch*.
- Toolkit duurzame gebiedsontwikkeling, *Met 20 bouwstenen naar een energieneutraal gebied; gids voor initiatiefnemers en projectleiders*, Æneas, uitgeverij van vakinformatie bv, Boxtel, 2012, *in Dutch*.
- [www.energieinbeeld.nl](http://www.energieinbeeld.nl), retrieved October 2016, *in Dutch*



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Modern Buildings and Environmental Comfort – Reuse of Existing and Vacant Buildings

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**Abstract:** The incompatibility between the vacancy of built edifications and the demand for housing in the central region of São Paulo is the prime motivator of this work. The purpose of this article is to prove, through environmental-simulation software, as well as spatial and ergonomic analysis, how urgent it is to rehabilitate buildings produced between 1930 and 1964, for residential purposes. The methodology involved the selection of two commercial buildings which are currently in state of disuse, and whose typologies strongly resemble the majority of buildings constructed in the same period (and for the same purposes), so that the solutions explored in this research can be replicated. Through rehabilitation, these constructions have been improved and have had their qualities explored to the fullest, in order to contribute to their overall autonomy and energetic efficiency. The ergonomic performance was studied through the analysis of tasks in order to assure it is possible to realize both conventional and non-conventional tasks in the residential environment. The article concluded that the constructive characteristics of the buildings, ergonomic performance improvements and users' behavioral changes have a strong influence on the overall performance of the units, increasing the potential for housing in the center of the city.

**Keywords:** Retrofit. Environmental performance. Ergonomic comfort.

### Introduction

A compact urban space doesn't necessarily mean twenty-story buildings around every corner. In fact, exploring the possibilities of mixed-use buildings so that the infrastructure can be exploited to its fullest is what defines a city's body. Having a transportation system operating optimally not only reduces the average time of daily trips, but also renews parts of the city who have been neglected by public administration.

Although São Paulo's central area has a seemingly intense use, it is filled with under-used infrastructure, since its usage is four times bigger during the day than it is during the night. This can be explained by the fact that the central portion of the city holds 24% of all the jobs, while most of the workers come from peripheral regions (data collected from the 'Renova Centro' program). Besides, the current vacancy rate of this same area is close to 30%, which makes the possibility of rehabilitating these buildings stand out, once the infrastructure is already there. Requalifying them means recovering their dwelling characteristics, who have been lost due to the changes on the users' necessities and on the demands of the region itself. The environmental conditions of a construction can vary based on the changes on its surroundings: taller buildings can block ventilation; the increase of

motorized vehicles creates vocal stress, and the temperature rises thanks to both of these situations.

In that context, it is of great importance to analyze environmental comfort parameters while in conception of a new building or while evaluating an existing one. This analysis consists of *an individual perception concerning physical space, influenced by values of convenience, adequacy, expressivity, comfort and pleasure* (VIRILIO, 1993).

Apart from the users' demands, it is crucial to implement systems with low energy consumption, seeing that our planet has limited natural resources and we should preserve them.

### **Building-choice standards**

Some characteristics make themselves present in most of the constructions built at the time, such as the large gaps between columns, big sized windows, ceiling heights around three meters – all that made possible with the use of reinforced concrete. Furthermore, thick walls propitiate increased thermal inertia, or, in other words, they guarantee the temperature variation range is smaller inside the building than on the outside, avoiding exacerbated peak temperatures. This is one of the main constructive features of the buildings that date from the years of 1930 through 1960.

Since the scope of the edifications that are being dealt with includes only commercial and trade and services constructions, the stories are fairly unobstructed, which makes layout solutions quite simple. However, the purpose of this research is to keep the proposed spaces as flexible as possible, so that it is viable to answer to whatever demand the different domestic environments may present.

After observing which are the most recurring typologies in the city of São Paulo, with emphasis on abandoned or sub utilized edifications, two were chosen to be explored in this study. Through those typological patterns it is intended to come to adaptable solutions to these buildings. From this, some of the most common characteristics inside these two typologies were listed, such as: mixed use; presence of commercial units on the ground floor; remaining floors holding various services; vertical circulation through stairs and elevators. Those characteristics helped narrowing down which would be the studied constructions. Following the described steps, two buildings were chosen, one of them located at Paula Souza Street and the other one at Capitão Salomão Street. For the purpose of this article, only the first one was explored, since it has a wider amount of possible solutions given the multiple obstacles and difficulties faced when attempting to rehabilitate it.

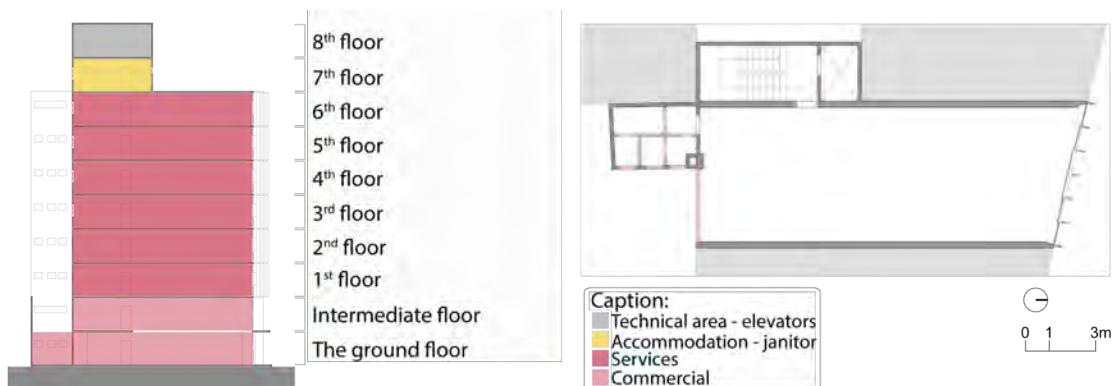


Image 1: Section with usage labels and typical floor plan of the building located on Paula Souza Street.

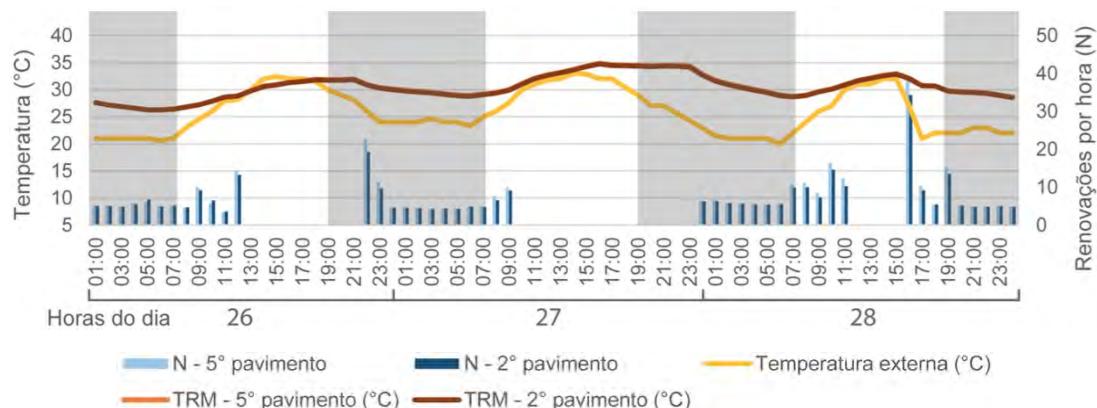
## Thermal simulations

Simplified models were elaborated for the virtual simulation of the studied objects using the software EDSL/Bentley Thermal Analysis Simulation, also known as TAS, which features thermal analysis simulation tools, available for academic use at the Laboratory of Environmental Comfort and Energetic Efficiency (LabAUT) in the Faculty of Architecture and Urbanism of the University of São Paulo. Moreover, the simulations were run only in the second and fifth floors of the model, contemplating all its different materials and openings. Since the original use of the building is different from the proposed one, the internal thermal loads were considered to be equivalent to the standard load in residential use in both the original and the designed situations, so that the differences showed by both simulations would come exclusively from the planned interventions.

The facade windows of the Paula Souza Street building have 20% openings while the remaining ones have 50% openings. The infiltration rate is equal to 1%. Moreover, the windows remain open as long as the temperature varies between 20°C and 30°C.

With this information in hands, four days were chosen for the simulations: days 26, 27 and 28: hot and sunny; days 10, 11 and 12: hot and cloudy; days 200 and 202: cold and sunny; days 187, 188 and 189: cold and cloudy. The results shown relate exclusively to the hot and sunny days, which are the most critical in the city of São Paulo.

Graphical analysis was generated for the construction's original situation concerning external and internal temperatures (average radiant temperatures - TRM) and natural ventilation (**N** air renovations per hour).



Graph 1: Results of the simulation made through the TAS software regarding days 26, 27 and 28 (hot and sunny) for the second and fifth floors of the original Paula Souza Street building. Elaborated by the author.

Observing the graphic above, it is clear to see the how the internal temperature is always higher than the external temperature. This happens due to the buildings large, unobstructed and north-facing openings, which generate great heat gain through direct radiation during most of the day. As a result of the edification's huge thermal mass, the TRM curves regarding internal environments show smaller variation, which represents more stable temperatures.

In an attempt to diminish excessive heat gain around noon (when there is the most solar radiation), horizontal *brisés* were installed on the facade, once direct incidence is the biggest contributor for temperature increase. However, on winter days, this radiation comes in handy, since it keeps the inside warmer than the outside. The elements of protection consist of 30 centimeter stems with 64 centimeter gaps between each of them, according to the studies of Uzum (2017).

## The Ergonomic Studies

As it has been mentioned, when it comes to ergonomic analysis the studied buildings can be easily reorganized in many ways, given their lack of obstructions due to the reinforced concrete structure. Seeking to improve thermal comfort, the ergonomic designs aimed to favor the user's operation toward the control of incident sunlight and ventilation, and also keeping the elements isolated, so that there are no safety issues as a result of either improvising when using them or of lack of room for proper handling. The users are able to tilt the brises as well as control the size of the openings on the windows. This is very convenient, since it transforms each user's autonomy into a tool to have the best possible internal conditions.

The rooms designed to be living/dining rooms were planned to answer to whichever demands the dwellers might have, even to complement their income, such as having a home office, a place to do craftwork, cooking, etc. The kitchen was also arranged in a less sealed way than usual – with no walls delimitating its boundaries – so that, with the proper layout, it can be easily adapted to receive a larger production of food than the ordinary household needs, since selling homemade treats is a common way to complement a family's income.

Several analysis were made on the circulation areas in order to prove the ergonomic quality of the proposal, ensuring every possible trajectory is safe and free of any discomfort. This also guarantees access to the windows and to the lighting control elements, reassuring the user's independence. Moreover, there were studies made concerning the usage of furnishings and general household equipment according to Panero (2002), where areas are established based on the performance of tasks related to the aforementioned equipment, to assure the environment is safe and comfortable for regular use.

Furthermore, rooms of sporadic use such as the laundry were planned to be out of the units in both cases, on a common area, specifically on the roof. Beyond that, there is an idea to invite the dwellers to participate in a community garden located in the unsheltered area, also on the roof.

Two distinct forms of typical floor occupation were proposed for the Paula Souza Street building. The first one features two *kitchenettes* and the second possesses a single unit with three bedrooms. Having two types of occupation and being able to alternate them throughout the stories makes it possible to attract a wider range of people who might want to live in the center of the city.

There is also the proposition for an atrium, since the edification has a very lengthy floorplan that prevents light and ventilation from reaching certain areas in adequate amounts. It would allow more flexibility regarding not only layout possibilities but also the number of units per level.

Furthermore, the unit with three bedrooms was planned so that it can shelter people who need a wheelchair, having the appropriate widths, turning radius and extra space on strategic sports for one to maneuver a wheelchair independently throughout the whole apartment.

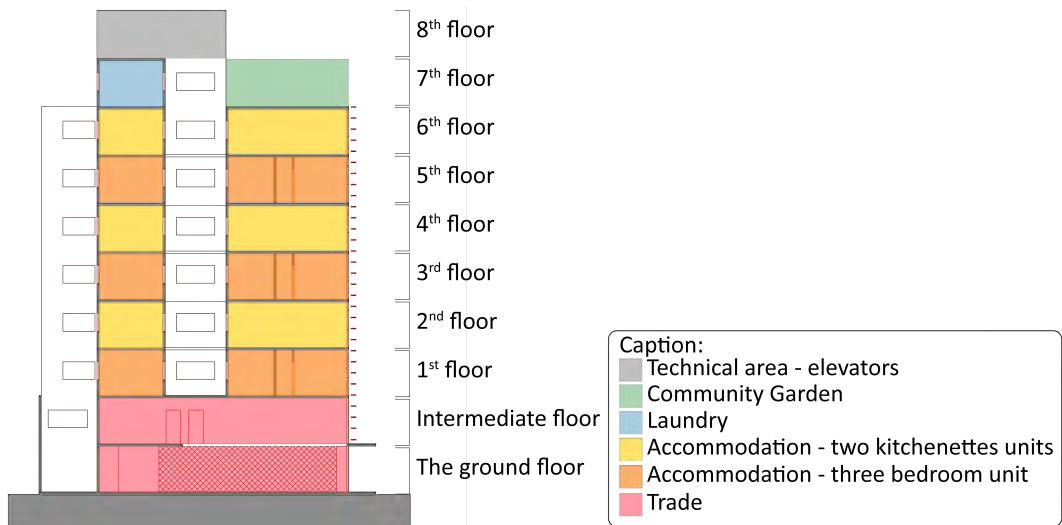


Image 2: Longitudinal section portraying the proposed usage for the Paula Souza Street building. Drawing made by the author.

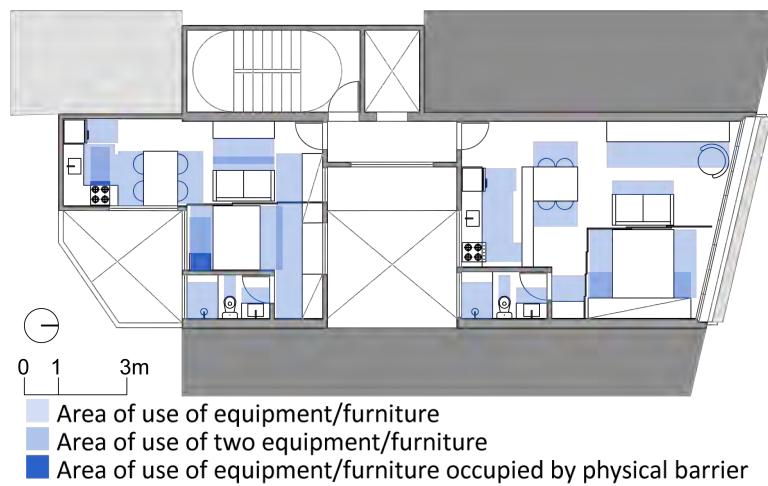


Image 3: Typical floorplan for the rehabilitation proposal, featuring two residential units of the Paula Souza Street building, with highlights on layout and household equipment usage areas. Drawing made by the author.

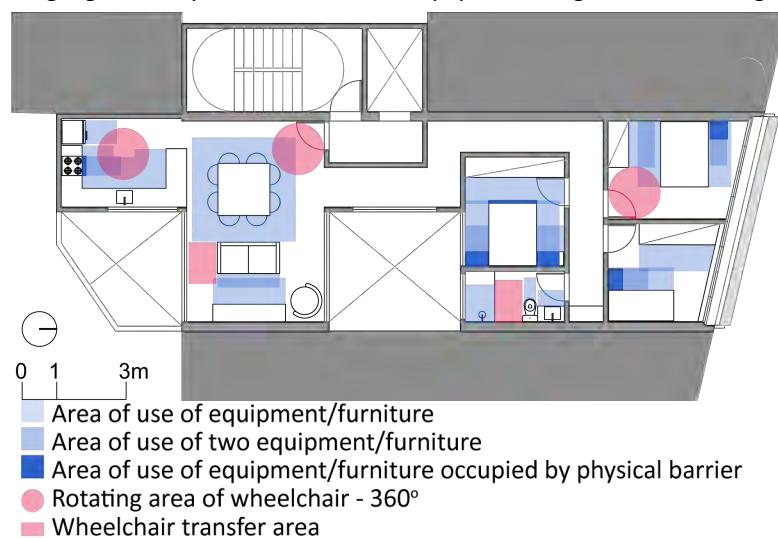


Image 4: Typical floorplan for the rehabilitation proposal, featuring one residential unit of the Paula Souza Street building, with highlights on layout and household equipment usage areas. Drawing made by the author.

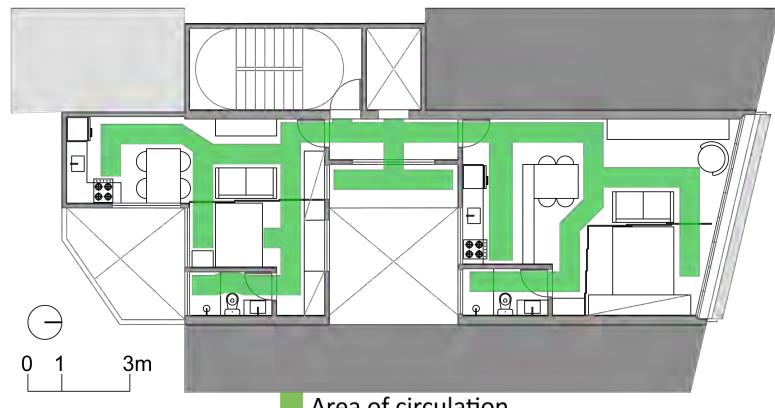


Image 5: Typical floorplan for the rehabilitation proposal, featuring two residential units of the Paula Souza Street building, with highlights on layout and internal transit areas. Drawing made by the author.

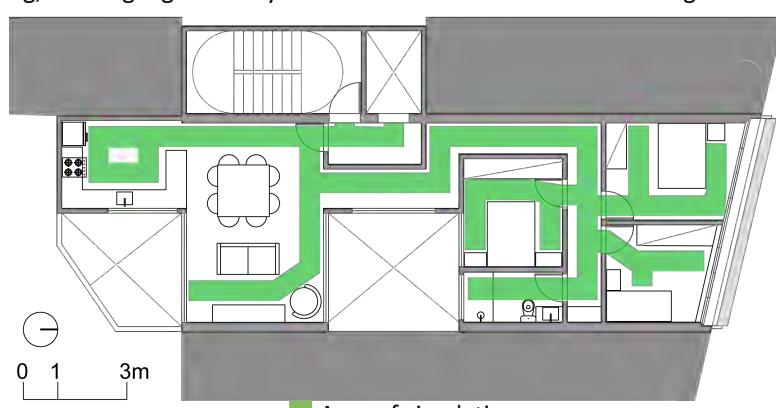


Image 6: Typical floorplan for the rehabilitation proposal, featuring one residential unit of the Paula Souza Street building, with highlights on layout and internal transit areas. Drawing made by the author.

### Proposals: Thermal Evaluation

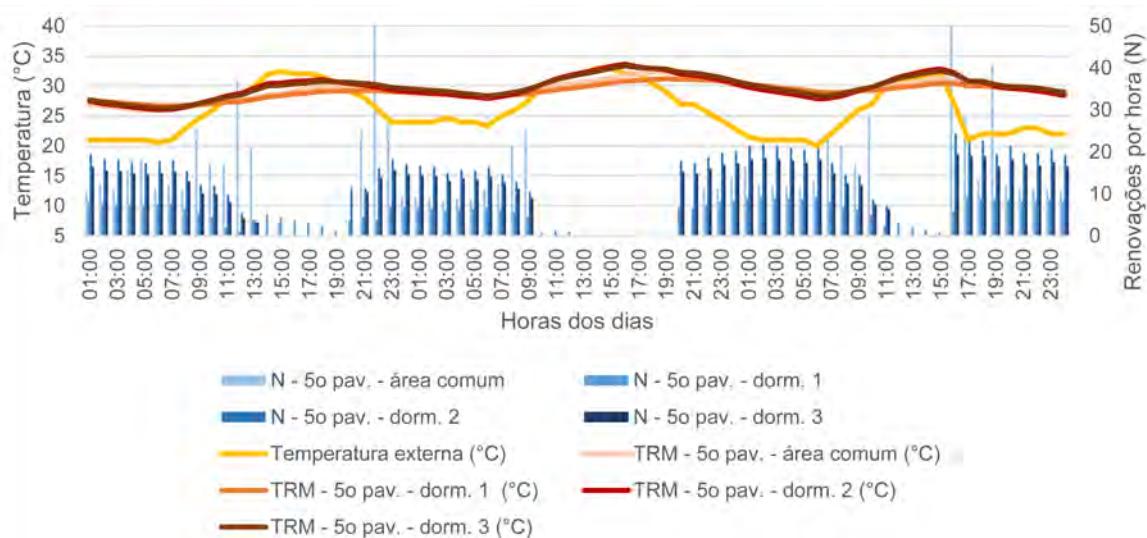
After applying the imagined conditions to the model, the simulations prove how effective these changes can be when it comes to thermal comfort. The gathered results were grouped in units, that is, each graph shows outcomes for each unit, in order to make them visually neat.

The material, climatic and thermal parameters were identical to the ones used in the previous simulations. Moreover, the same days of the year were analyzed. The hot and sunny period was picked for review because it features intense direct solar radiation, which is what contributes the most for internal temperature increase on north-facing facades.

The simulated environment portraying a three-bedroom unit on the fifth floor of the Paula Souza Street building was enumerated as follows:



Image 7: Labels for each room on a three-bedroom unit of the Paula Souza Street building. Drawing made by the author.



Graph 2: Results of the simulation made through the TAS software regarding days 26, 27 and 28 (hot and sunny) for the fifth floor of the Paula Souza Street building. Elaborated by the author.

The simulated environment portraying two *kitchenettes* on the fifth floor of the Paula Souza Street building was enumerated as follows:

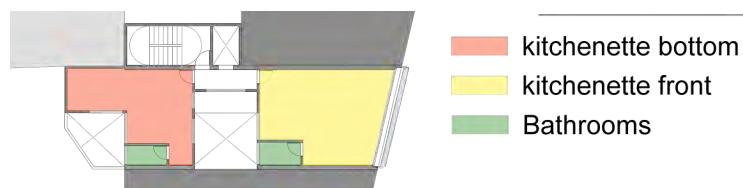
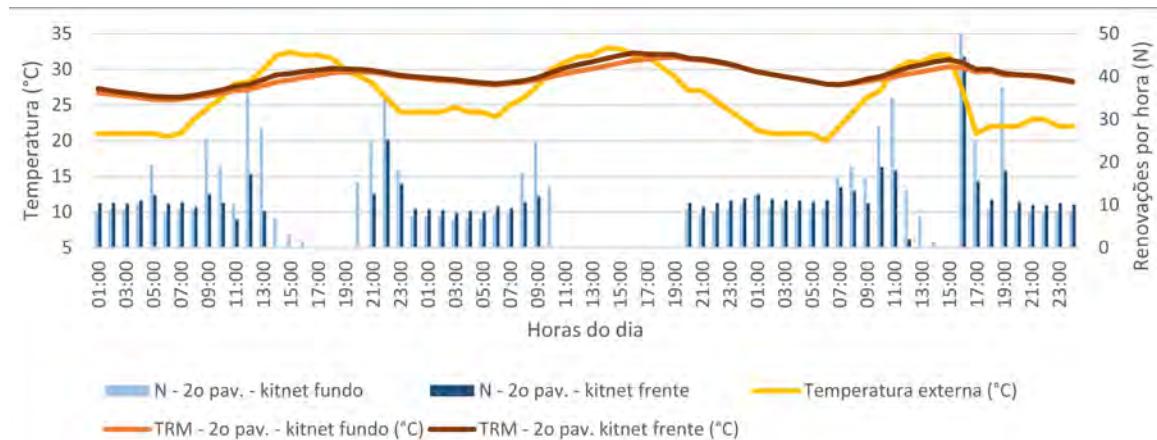


Image 8: Labels for each room featuring two kitchenettes of the Paula Souza Street building. Drawing made by the author.



Graph 3: Results of the simulation made through the TAS software regarding days 26, 27 and 28 (hot and sunny) for the second floor of the Paula Souza Street building. Elaborated by the author.

The aftermath shows how the temperature curves referring to the internal rooms tend to flatten, even staying below the outside temperature curve during the hottest periods of the day.

When comparing the results gathered by the simulation model, it is clear to see the difference between the original situation and the proposed one, since the atrium propitiates huge increment concerning natural ventilation throughout the whole edification. The temperatures have less abrupt changes, mainly on the critical hours of direct solar radiation, seeing that among the hours of the day, there are many on which the outside temperature exceeds the one on the inside (on the model with the applied modifications), not alike what

the original model simulation reveals about itself – the number of hours with inner temperature lower than outer temperature are virtually nonexistent in the former condition.

## Conclusion

In possession of the outcomes of this study, it was possible to evidence how well the buildings created at this time can be readapted, given their constructive particularities that provide good thermal characteristics as well as versatile layout solutions. Adding this to the great stock of idle buildings in the central region of São Paulo, the rehabilitation of this type of edification becomes not only possible, but also necessary. This idea can be supported by the fact that there are many illegal occupations in buildings with similar characteristics, even with very little salubrity and precarious living conditions.

There is a great benefit from allying constructive aspects to ergonomic ideas that allow users to exercise full control of openings and a project that aims for softened effects when it comes to direct solar incidence. Moreover, two different unit formats have been presented, so that it is viable to house as many different families as possible. Since the majority of the units were thought to be accessible for disabled people, they can also fit the elderly who can develop special needs or even someone who has been through some kind of trauma and might need a wheelchair temporarily.

Through a different point of view, although still concerning the same buildings, it was possible to re-evaluate the need of a personal laundry room for each unit, since it is something that exists based on cultural reasons only. Once the units have limited areas, it seemed like a reasonable solution to relocate the laundry onto a common space, since it doesn't have an intimate essence as most rooms in a house. Being the building thought to house different types of families, a common laundry room shouldn't have concentrate usage, which answers best to everyone's needs. The same applies to the community garden, although it has an even greater potential of bringing people closer, besides creating free food.

It is also important to notice that the proposals elaborated have a good chance of being replicated, once the buildings in the region have very similar characteristics to the ones analyzed in this research. That being said, this paper comprehends possibilities which may work as future reference for interventions and rehabilitations such as this one, in hope to encourage more idle buildings to be readapted not only in São Paulo but in every city lacking appropriate dwellings close to the majority of their work places.

## References

- ABNT, NBR 9050 - Acessibilidade a edificações, mobiliário, espaços e equipamentos urbanos. 2015.
- Gonçalves, J. C. S., Bode, K. (2015). *Edifício Ambiental*. São Paulo: Oficina de textos.
- Kronka Mülfarth, R. C. (2015). *A reocupação de edifícios multifamiliares no centro de São Paulo, uma reflexão sobre a questão ergonômica*. In *O Edifício Ambiental*. São Paulo: Oficina de Textos.
- Kronka Mülfarth, R. C. (2013). *Sustentabilidade e Mobilidade: o desenho urbano e as questões relacionadas com a qualidade ambiental*. IV SIMPGEU - Simpósio de Pós-Graduação em Engenharia Urbana e I ENURB – Encontro Nacional de Tecnologia Urbana.
- Panero, J., Zelnik, M. (2001). *Dimensionamento Humano para Espaços Interiores*. Barcelona: GG.
- Uzum, M. dos S. D. (2011). *A requalificação de edifícios altos residenciais no centro da cidade de São Paulo: em busca de qualidade ambiental*. Dissertação de Mestrado. Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo.
- Uzum, M. dos S. D. *Conforto térmico e luminoso para habitação econômica: O potencial de edifícios altos existentes nos bairros centrais de São Paulo*. Tese de Doutorado. Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo. Publication "in press".



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Development of Generic Energy Efficiency Category: An Accreditation Comparison of Different Green Rating Systems for a Case Study in Canada

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**Abstract:** As part of developing a generic rating system for green constructions, this research introducing a comparison between the credits owned by different international rating systems and the generic rating category developed for energy efficiency. One of Concordia University campus buildings in Canada has been simulated using the IES-VE simulation tool to calculate energy consumed applying different constraints of various rating systems against the developed one. The generic developed category describes international credits that suit those mentioned in LEED USA, BOMA BESt Canada, BREEAM UK, Greenship Indonesia, CASBEE Japan, BEAM Hong Kong, and Green Building Index Malaysia rating systems. By considering five rating systems, the case building fails to achieve the prerequisites of energy category in LEED USA and Canada, Greenship Indonesia, Green Building Index Malaysia, and the developed rating system, while it is rated in the case of Hong Kong. Hence, a comparison is conducted to stand for the amount of energy saving required to achieve the credits between each of the five selected rating systems and the developed one. The results show that the generic developed energy category surpasses the other rating systems as it requires more energy conservation for the building to be rated. The difference between the energy saving needed in the developed rating system and the existing ones ranging between 2,181.11 MWh /year, and 6,503.71 MWh /year.

**Keywords:** Sustainability rating systems, energy performance, LEED, BREEAM, HK-BEAM

### Introduction

The building sector accounts for 32% of global energy consumption, 19% of energy-related CO<sub>2</sub> emissions, 51% of global electricity consumption, and 9% of the world petroleum consumption (IIASA, 2012; IPCC, 2014). Moreover, building sector emits per electricity use 8.6 GTCO<sub>2</sub>-eq., 0.4 GTCO<sub>2</sub>- eq. CH<sub>4</sub>, 0.1 GTCO<sub>2</sub>- eq. N<sub>2</sub>O, 1.5 GTCO<sub>2</sub>- eq. Halocarbons (CFC and HCFC) and 35-40% of CO<sub>2</sub> emissions from the use of fossil fuels (Urge-Vorsatz et al., 2007).

There are many rating systems throughout the world that aim to assess sustainability. However, there are noticeable variations between these systems of the same grade or rating, such that BREEAM Excellent and LEED Platinum, are not equivalent in terms of sustainability performance. Therefore, it difficult for buildings' stakeholders, especially property investors who purchase buildings in different countries, to compare the sustainability performance of their buildings on a consistent basis (Dixon et al., 2008). Also, there is no unified concept or definition of sustainability assessment attributes that can be utilized to express the key aspects of sustainability and to be adopted in different regions (Baharetha et al., 2012; Banani

et al., 2013). Moreover, previous studies highlighted the importance of developing an international system to mitigate the global impact of buildings on our environment (Reed et al., 2009; Todd and Geissler, 1999). Hence, it is needed to utilize a global thinking concerning sustainability of buildings by using globally working rating systems.

Energy is considered the most important criterion in the sustainability assessment (Al-Geelawe and Mohsin, 2015; Berardi, 2012; Perez-Lombard et al., 2008; Schwartz and Raslan, 2013). As a part of a proposed generic rating tool (Mahmoud and Zayed, 2017), the energy category is selected to spotlight on the generic concept of sustainability assessment. This research highlights 1) the proposed energy assessment attributes, 2) comparison between the proposed attributes and the others of different rating systems, 3) energy consumption and carbon emissions of a case through simulation in five regions, and 4) the results of simulation showing the amount of energy that can be conserved using different systems and the proposed one.

## **Methodology**

The methodology is divided into four parts: first, introducing the proposed energy factors for the developed energy category as a part of a proposed generic rating tool. Second, conducting a comparison between the proposed method and some existing rating tools to stand for the attributes that were overlooked in these tools. Third, developing a simulation utilizing IES VE software to stand for the impact of regional environment on the energy consumption, even using the same building. Finally, the fourth part, performing a comparison between the proposed assessment method and five existing ones concerning energy consumption and degree of conservation in energy.

### ***Proposed energy category***

The primary targets of the energy assessment are reducing both the energy consumption and the unwanted impacts of the life cycle of buildings. The proposed energy category includes four factors as depicted in Figure 1. The first is energy performance measures percentage of reduction in energy use through the minimum required energy performance, and optimizing energy performance. Second, provision of energy management evaluates the existence of energy operating plan for the building, energy audit, energy monitoring and metering for the operated equipment to stand for their energy consumption, commissioning and testing for analysing energy demand and end-uses and to provide an ongoing commissioning, building automated system which monitors and controls all the building systems, emissions reduction then reporting them to identify building performance parameters which reduce conventional energy consumption and quantify these reductions, and finally, sustainable maintenance to ensure that all the systems will perform in an efficient way according to the designed building maintenance. Third, energy efficient systems estimates using of efficient systems to reduce energy consumption such as: interior lighting and zone control, renewable energy systems, energy efficient circulation system and efficient ventilation in car parks. Finally, energy efficient equipment assesses the amount of utilizing energy-efficient appliances and cloth drying facilities, energy-efficient AC equipment and high-efficiency equipment.

A comparison was conducted between eight rating systems selected from the World Green Building Council member list (Worldgbc, 2016) concerning the proposed assessment attributes. The already established green building tool is the key selection criteria of these eight rating tools. The eight rating tools are LEED (USGBC, 2009), BREEAM (BRE, 2015), HK-BEAM (HK GBC, 2012), BCA green mark (BCA, 2012), Greenship (GBC Indonesia, 2012), Green

Building Index (GBI, 2011), BOMA BEST (BOMA Canada, 2013), and CASBEE (JaGBC, 2008) as shown in Table 1. The comparison aims to spotlight on the fundamental attributes and the overlooked ones that affect the sustainability of existing buildings, which should be integrated into the developed rating tool. As shown in Table 1, all the tools include the *provision of energy management* and *energy efficient systems* factors in their assessment framework, contrarily, *energy efficient equipment* has the lowest share.

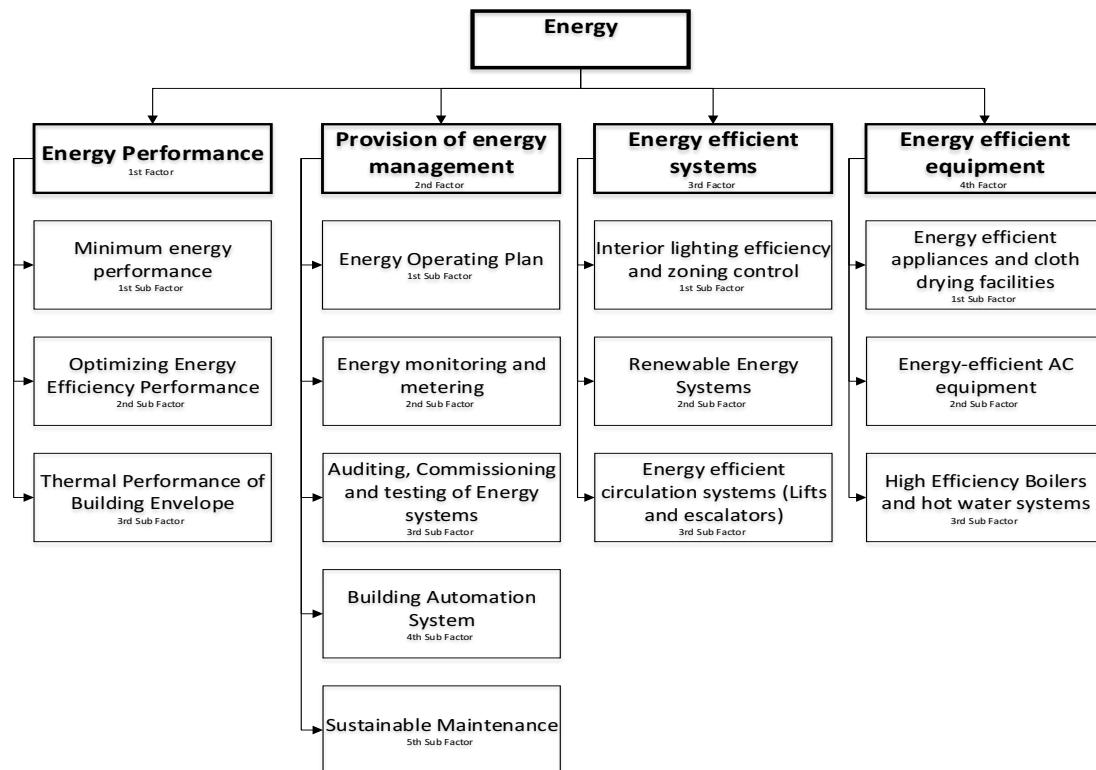


Figure 1. Proposed energy criterion and its related factors and sub factors

Table 1. Energy use criteria comparison among eight rating tools

Criteria factors and subfactors of the proposed System	LEED	BREEAM	BCA Green	HK BEAM	Green Building	Green Globes	Green ship	CASBEE (Japan)
<b>Energy Criterion</b>								
Energy Performance Factor	•	•	•	•	•	•	•	
Minimum Energy Performance	•			•	•		•	
Optimizing Energy Efficiency Performance	•	•		•	•	•	•	
Evaluation of Thermal Performance Reduction of Building Envelope			•			•		
Provision of Energy Management Factor	•	•	•	•	•	•	•	•
Energy Operating Plan	•		•	•		•	•	
Energy Monitoring and Metering	•			•	•	•	•	•
Commissioning and Testing Energy Systems	•	•		•	•	•	•	
Building Automation System, or Energy Management System (EMS)	•				•			
Sustainable Maintenance					•		•	
Energy Efficient Systems Factor	•	•	•	•	•	•	•	•
Interior Lighting Efficiency and Zoning Control.	•	•	•	•	•		•	
Renewable Energy Systems	•	•	•	•	•	•	•	•
Energy Efficient Circulation Systems (Lifts and escalators)			•					
Energy Efficient Equipment Factor		•	•	•		•	•	•
Energy Efficient Appliances and Cloth Drying Facilities				•				
Energy Efficient AC Equipment		•	•	•			•	•
High Efficiency Boilers		•				•		

### **Case study building**

The case study building is located in Montreal, Quebec, Canada, which is one of the Concordia University buildings called the EV Building, which accommodates the engineering departments and the art departments. The gross building area is 54,335 m<sup>2</sup> which comprises sixteen above floor levels and three basement levels. A BIM model using Revit software was developed to extract different data that will be utilized in the sustainability assessment such as: the floor area of each room, the gross area of each floor, the total area of the entire building, the area and material of walls and partitions, the cladding area and type, number of fixtures in each bathroom, the height of each floor, and generating XML file to develop the IES model. The GBXML model has been exported to IES VE software to perform energy simulation which is based on the actual size and the materials of the building as shown in Figure 2. The developed IES model is utilized to stand for the building energy consumption in yearly and monthly as shown in Figure 3 and Figure 4 respectively.



Actual Building

BIM model (Revit)

IES VE Model

Figure 2. Case study different modeling stages

### **Simulation results**

A simulation of the EV building has been performed for one city in each of the seven different countries as illustrated in Figure 3 which are: Hong Kong, China; Jakarta, Indonesia; New York, Malaysia; Cairo, Egypt; London, England; Kuala Lumpur, Malaysia; and Montreal, Canada. The accuracy of the simulation model was compared to the actual data of energy consumption. The actual total energy consumption of the building is 23,000 MWh, while, according to the simulation results and as shown in Figure 3 is 23,656 MWh with an error of 2.85% which increase the confidence in the results that has been extracted from the simulation. Consequently, according to Figure 3 and Figure 4, the total energy consumption (in MWh) in the cold weathered cities, i.e. Montreal and New York, is much higher than the other warm weathered countries due to the high increase in the demand for space heating and hot water provision. These energy demands are reflected in the carbon emissions which are the primary sources of GHG which result in increasing the global warmth. Unfortunately, in all the cities, a single building is responsible for high carbon emissions. However, the cities with the highest energy consumption have the largest share of GHG emissions shown in Figure 5.

Further, based on the simulation results, a comparison has been conducted between five rating system and the proposed one to determine the degree of improvement in energy performance that the proposed model can perform when compared with each of the selected rating systems as illustrated in Table 2. These rating systems are LEED, USA; LEED, Canada; GreenShip, Indonesia; Green Building Index, Malaysia; and HK-BEAM, Hong Kong. These five

rating systems have been selected as they utilize energy consumption in their assessment not the amount of carbon dioxide emissions as BREEAM.

Moreover, all the rating systems in Table 2 except Green Building Index have minimum energy performance prerequisites that obligate an achievement of a certain amount of energy to start the assessment. The proposed rating system requires a fulfillment of a 19 % of energy conservation above a baseline which is the median of weathered normalized energy use intensity (EUI) in the Energy Star Portfolio Manager website. This concept of assessment is also adopted in LEED. The rationale for using this method in evaluation in the proposed that the Energy Star Portfolio Manager possess a large library of weather stations and building baseline database of most of the countries of the globes with different weather stations in each city. Additionally, the aim of the proposed rating system is to set a unified basis of assessment in most of the sustainability categories, especially the energy category, so based on this argue, the energy simulation and the EUI are used for the assessment.

The baseline EUI for each of the USA, Canada, Indonesia, Malaysia, and Hong Kong are 31,427.16; 16,403.85; 31,392.07; 31,430.63; 31,430.63 MWh/ year respectively. The current EUI assessment of the five countries, according to simulation, are higher than the median with 0.8 %, 86.7 %, 4.6 %, 3.8 %, and 23.3 % respectively. Besides, the energy category is not rated in three out of the five rating systems, as the energy performance of the building does not fulfill the prerequisites except for the Green Building Index and HK\_BEAM. While applying the proposed rating for assessing energy category implementing the simulated consumption of the five countries, the energy category is not rated in four countries using the developed rating tool while it is rated in Hong Kong. The amount of energy reduction required for the building to be rated using the developed rating system is 5,971.16, 17,338.9, 7400.53, and 7,166.75 MWh/ year, while the amount of energy reduction required to be rated with the other four rating systems are 3,790.05; 13,393.3; 896.82; and 4,872.78 MWh/ year. Consequently, the proposed method surpasses the other rating systems in energy reduction and is capable of conserving 2,181.11; 3,945.60; 6,503.71; and 2,293.97 MWh/ year.

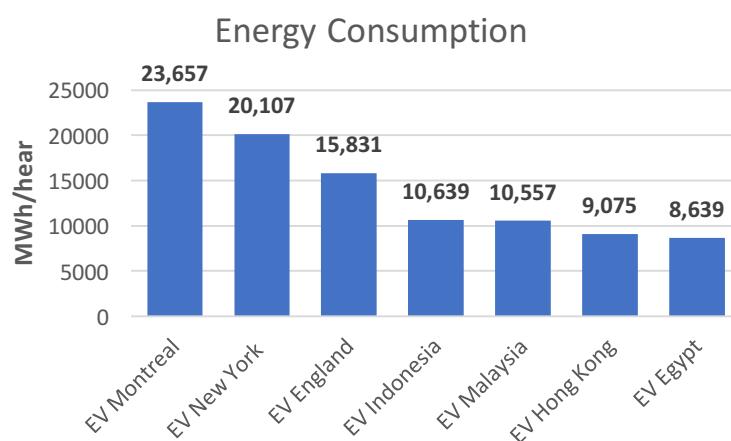


Figure 3. Total energy consumption for seven countries

## Monthly Energy Consumption per country

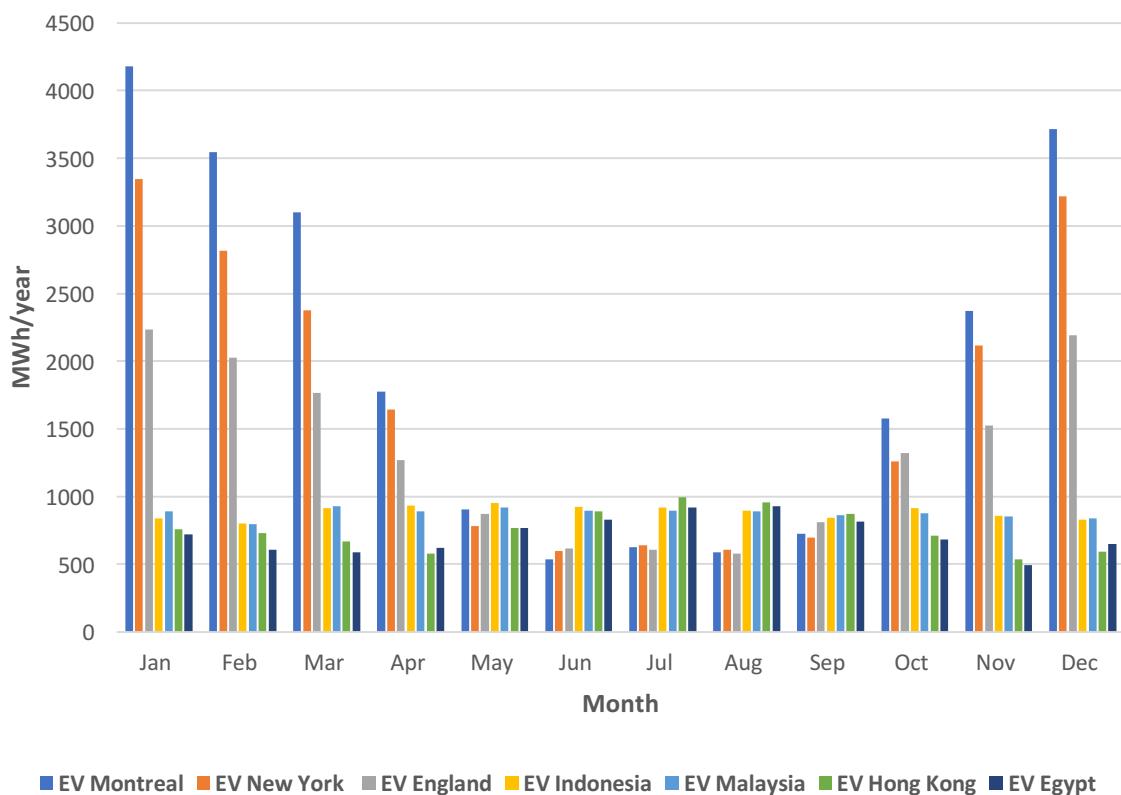


Figure 4. Monthly basis energy consumption for seven countries

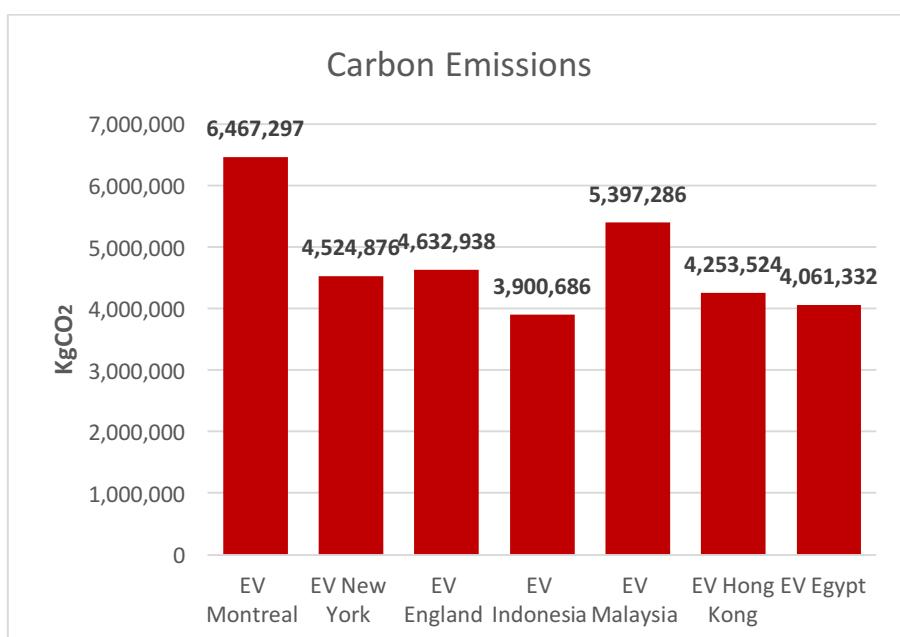


Figure 5. Annual Carbon dioxide emissions

Table 2. Comparison of Energy Assessment – Developed Model vs. Existing Rating Systems

	USA		Canada		Indonesia		Malaysia		Hong Kong	
	LEED	Proposed System (EUI)	LEED Canada	Proposed System (EUI)	Greenship	Proposed System (EUI)	Green building Index	Proposed System (EUI)	HK-BEAM	Proposed System (EUI)
Energy consumption (MWh)	20,107	31,679	23,657	30,626	10,639	32,836	10,556	32,626	9,0745	24,101
Baseline consumption (MWh)	19,948	31,428	12,671	16,404	9,472	31,393	5,683	31,431	13,612	31,422
Compared to baseline	0.8% higher	0.8 % higher	86.7 % higher	86.7 % higher	9.5 % higher	4.6 % higher	47 % higher	3.8 % higher	33.3% lower	23.3 % lower
Existence of prerequisite	Exist	Exist	Exist	Exist	Exist	Exist	Not Exist	Exist	Exist	Exist
Prerequisite statement	19% above baseline	19% above baseline	19% above baseline	19% above baseline	250kWh/m <sup>2</sup> . yr Or 5% reduction in next 6 month	19% above baseline	-	19% above baseline	150 % higher than baseline	19% above baseline
rating status	Not rated	Not rated	Not rated	Not rated	Not rated	Not rated	Rated	Not rated	Rated	Rated
Energy value required	16,158	25,456	10,264	13,287	9,472	25,428	-	25,459	-	-
Energy reduction required to achieve baseline (MWh)	3,790	5,971	13,393	17,339	897	7401	4,873	7,167	-	-
Achieved score (1)	-	-	-	-	-	-	14	-	31	18
Max. available score (2)	35	-	35	-	36	-	38	-	38	63
Percentage between (1) and (2)	-	-	-	-	-	-	28.6 %	-	81.6 %	29.5 %

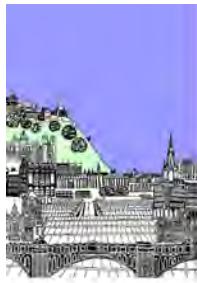
## Conclusion and discussion

This study aims to spotlight on the importance of considering globally working rating tools to set a unified method of sustainability assessment while considering the regional variations. Also, this study showed a part of a proposed generic rating tool, focusing on the energy category and describing its assessment attributes. The methodology explored various aspects. First, it demonstrated a comparison that had been conducted between the proposed rating tool and eight existing ones, showing the attributes that were covered in the proposed one. Second, a simulation utilizing a case study building was performed in different countries which illustrated how the regional variations could affect the energy consumption drastically even using the same building. This highlighted the importance of using a consistent method

of assessment to compare the energy performance of the buildings in different regions, which is the urgent demand of many building's stakeholders where ever they want to compare the performance of their widely-spread properties using an international language. Finally, the third part was a comparison had been conducted between the proposed assessment method to be used globally, and different rating tools in various regions, showing that the proposed method can compete the existing tools in achieving more energy conservation which is the main aim of the sustainability assessment tools.

## References

- Al-Geelawe, E.K. & Mohsin, A.H. (2015), "Implementing Sustainability Strategies in the Design of Buildings", *Applied Research Journal*, vol. 1, no. 10, pp. 478-489.
- Baharetha, S. M., Al-Hammad, A. A., and Alshuwaikhat, H. M. (2012). "Towards a Unified Set of Sustainable Building Materials Criteria." Proceeding of the International Conference on Sustainable Design, Engineering, and Construction, ASCE, Fort Worth, Texas, November 7-9, 732-740.
- Banani, R., Vahdati, M., and Elmualim, A. (2013). "Demonstrating the Importance of Criteria and Sub-criteria in Building Assessment Methods." *Journal of Sustainable Development and Planning VI*, 173, 443-453.
- BCA (2012), *BCA Green Mark for Existing Non-Residential Buildings*, version 3.0, Building and Construction Authority, Singapore.
- Berardi, U. (2012), "Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings", *Sustainable Development*, vol. 20, pp. 411-424.
- BOMA Canada (2013), *BOMA BESt Assessment Overview: BOMA Building Environmental Standards (Office Module)*, BOMA Canada, Canada.
- BRE 2015, *BREEAM In-Use International: Technical Manual*, SD221 - 1.0:2015, BRE Global Ltd, Hertfordshire.
- Dixon, T., Colantonio, A., Shiers, D., Reed, R., Wilkinson, S., and Gallimore, P. (2008). "A Green Profession? A Global Survey of RICS Members and Their Engagement with the Sustainability Agenda." *Journal of Property Investment and Finance*, 26(6), 460-481.
- GBC Indonesia (2011), *Greenship Existing Building for Existing Building: Benchmark Summary*, Version 1.0, Green Building Council Indonesia, Indonesia.
- GBI (2011), *GBI Assessment Criteria for Non-Residential Existing Buildings*, First edition, version 1.1, Green Building Index, Kuala Lumpur.
- HK GBC (2012), *BEAM Plus: Existing Buildings*, Version 1.2, BEAM Society Limited., Hong Kong.
- IIASA (2012), *Global Energy Assessment: Toward a Sustainable Future*, Cambridge University Press, Cambridge.
- IPCC (2014), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York.
- JaGBC (2008), *CASBEE for New Construction: Comprehensive Assessment System for Building Environmental Efficiency Technical Manual*, 2008th, Institute for Building Environment and Energy Conservation (IBEC), Japan.
- Mahmoud, S. & Zayed, T. (2017), "An Integrated Sustainability Assessment Tool Framework", *Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17)*, April 2 – 4, pp. 1-8.
- Reed, R., Wilkinson, S., Bilos, A. & Schulte, K. (2011), "A Comparison of International Sustainable Building Tools – An Update", The 17th Annual Pacific Rim Real Estate Society Conference, Gold Coast, Australia.
- Schwartz, Y. & Raslan, R. (2013), "Variations in Results of Building Energy Simulation Tools, and their Impact on BREEAM and LEED Ratings: A Case Study", *Energy and Building*, vol. 62, pp. 350-359.
- Todd, J.A. & Geissler, S. (1999), "Regional and Cultural Issues in Environmental Performance Assessment for Buildings", *Building Research and Information*, vol. 27, no. 4-5, pp. 247-256.
- ürge-Vorsatz, D., Harvey, L.D.D., Mirasgedis, S. & Levine, M.D. (2007), "Mitigating CO<sub>2</sub> emissions from energy use in the world's buildings", *Building Research & Information*, vol. 35, no. 4, pp. 379-398.
- USGBC (2009), *LEED Reference Guide foGreen Building Operations and Maintenance for the Operations and Maintenance of Commercial and Institutional Buildings*, 2009 Edition, U.S. Green Building Council, Washington, DC.
- Worldgbc 2016, , World Green Buiding Council. Available: <http://www.worldgbc.org/member-directory> [2016, April/05].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## An online decision-making guide for the sustainable refurbishment of Belgian Walloon schools

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**Abstract:** Belgian Walloon's school building stock is old and energetically inefficient. The major obstacles to their renovation are the lack of financial means and the difficulty to coordinate renovation works with school activities. This paper presents an online guide developed for helping managers and architects in this school refurbishment. The objective is to lead choices towards reduction of environmental impacts as well as improvement of well-being, health and working performance of occupants. The tool is available online since summer 2016 (in French) at [www.renovermonecole.be](http://www.renovermonecole.be).

**Keywords:** school, renovation, retrofit, children comfort

### Introduction

Most of Belgian Walloon schools are old. High ambitions are often pursued for new school buildings but the most efficient way to reduce environmental impacts of schools is surely to accelerate and improve the renovation process of existing ones. The objectives of this research were (1) to help managers and designers to integrate environmental and well-being objectives in any school renovation process, with a long term high quality level standard, and (2) to create a tool that considers specificities of schools, renovation and specific context of Wallonia.

### Context of school buildings and school renovation process

The design of the online guide described in this paper started with an analysis of context, regarding both existing buildings and usual renovation process.

First, we observed that Belgian Walloon school buildings stock is characterized by:

- three education systems (free, Federation Wallonia Brussels official, municipal/provincial official)
- a great variety of building types and scales following the location and the level of teaching (infant, primary, secondary). There is no useful database on Walloon schools. The complicated context of three different education systems and a lack of financial means explain the situation.
- a globally poor energy efficiency (see Fig.1)

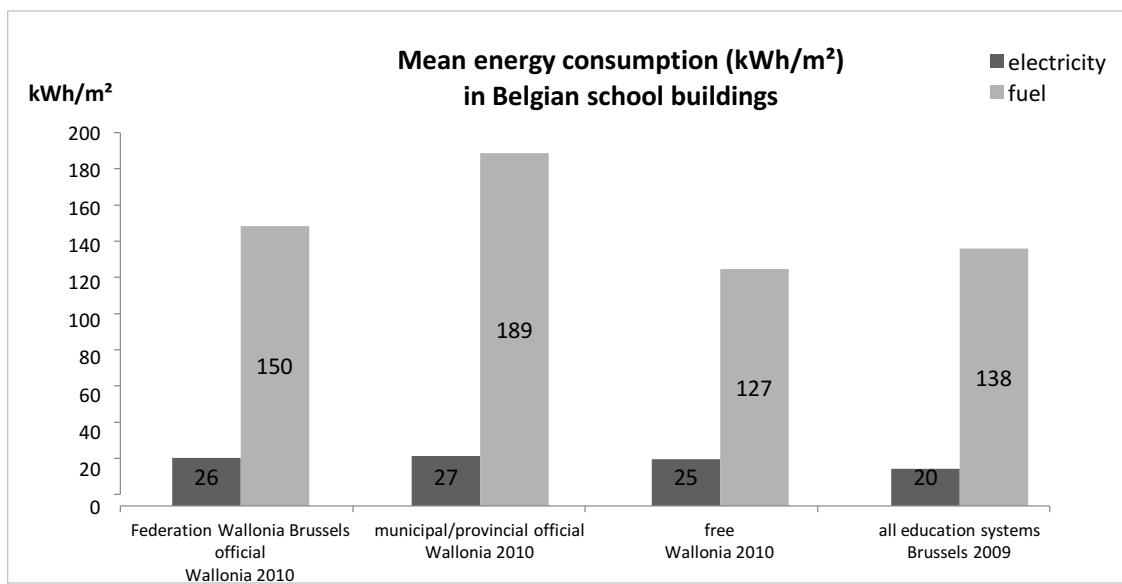


Figure 1. Mean energy consumption in Belgian school buildings, depending on the education system and the location.

Meetings with school directors, school building managers in the public sector (municipalities or Federation Wallonia Brussels) and architects specialized in school design helped to clarify specificities of school buildings and multiple challenges of school renovation (see Fig.2). We concluded that processes and situations differ from a school to another, from an educational system to another but all meet financial and organisational difficulties. Renovation work are usually carried out to answer a specific problem (roof leak, lack of space, heating system breakdown, fire safety rules...) and/or to benefit a specific opportunity (special funding, available competence...). Hard financial and organisational context, often coupled with old buildings lead to many emergency situations and partial renovation actions carried out with a lack of global long term vision and little concern about environment and occupants wellbeing. Tools and guidelines claiming for ambitious targets (zero energy buildings...) without considering the difficult context may miss the point because actors have a realistic and poor vision of their short term possibilities. And often, they consider that ambitious objectives are not possible to reach. Regarding motivations, reducing environmental impacts is rarely a primary objective. Energy consumption is mainly considered from a financial point of view. Reduction of water consumption, atmospheric pollution or waste or increasing biodiversity on school sites are almost never taken in account in renovation processes.

From visits and discussions with a “Facilitateur énergie dans les écoles”<sup>1</sup>, we may consider that:

- regarding heating systems, typical radiators systems with gas or fuel kettle is the most common system. Regulation is rarely performant and easy energy savings can be done there. This has been demonstrated with results of a PLAGE program<sup>2</sup> led on

<sup>1</sup> The « Facilitateur énergie dans les écoles » is an energy consultant of the Walloon region. He has a good global perception of schools situation thanks to his numerous visits of schools.

<sup>2</sup> PLAGE is a Local action plan for energy management. Such a program has been led with 110 schools in Brussels between 2009 and 2014.

110 schools in Brussels. In average, energy consumption for heating have been reduced of 21% during the action, mainly by improving heating systems regulation.

- many schools have no proper ventilation system. Hygienic ventilation is often only dependent on manual window opening. Therefore, CO<sub>2</sub> concentration is above advised threshold of 1000 ppm most of the time in Walloon classrooms.
- electric lighting is inefficient and visual comfort is rarely assured. Main causes are the old age of the installation and its lack of maintenance. Daylight, space and occupancy managements are strategies rarely implemented.

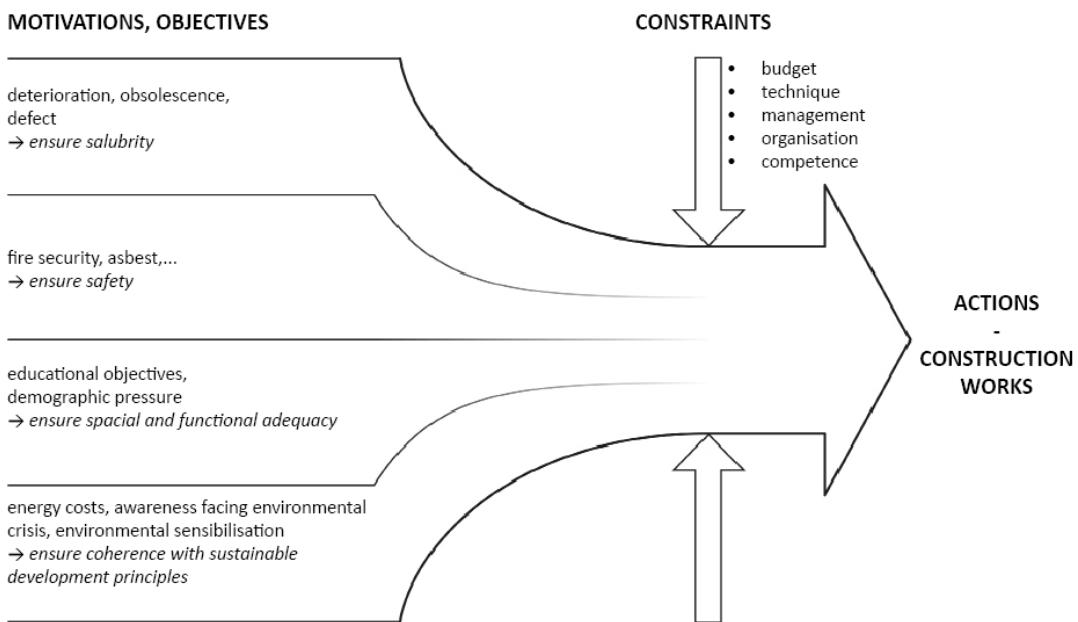


Figure 2. Identification of goals and constraints that lead to effective actions and renovation works in schools.

Last, from literature, links between the occupant comfort (thermal, visual, respiratory...) and its health, performance and well-being<sup>3</sup> have been showed. Furthermore, children appear to be more sensitive to bad conditions than adults. This is due to physical particularities (small body mass, low sweating capacities...) and to school activities (learning, new skills development...) (Wargocki and Wyon, 2006, Toftum et al, 2015).

Beyond the Walloon context, the following specificities of school buildings have been identified:

- low time occupation rate. Schools are usually occupied for 15-20% of the time since teaching schedules are mainly:
  - 8.00 to 16.00
  - 4.5 days/week
  - less than 38 weeks a year
- high space occupation rate (20-30 children/classroom). School surface ratio are 2.3-3.6m<sup>2</sup>/person (ratios for office buildings are 12-15m<sup>2</sup>/person).
- many different spaces types and functions: classrooms, eating room, technical workshops, library, offices, sport facilities, outside spaces...
- many different users: children from 2.5 to 20 years old, teachers, parents, administrative and technical workers...

<sup>3</sup> The word "well-being" is used in this paper to speak about comfort, health and learning/teaching performances.

- teaching and learning place: schools have a key role to play for our common future, with a possible leverage effect towards a more sustainable society

### Content of the online guide

The tool developed is an online guide called “Step by step towards a sustainable school”. It is free and available online at [www.renovermonecole.be](http://www.renovermonecole.be) since June 2016. Content is written in French. Expected users are school directors, school building managers and architects. Since this tool cannot have an influence on the financial and organisational means of schools, it was developed to adapt to the way renovation works happen to be carried out in reality. That is, step by step, with limited financial means (see Fig.3). The purpose is to enhance the global efficiency of renovation work done by improving actor's knowledge and competence regarding sustainable development principles applied to school buildings.

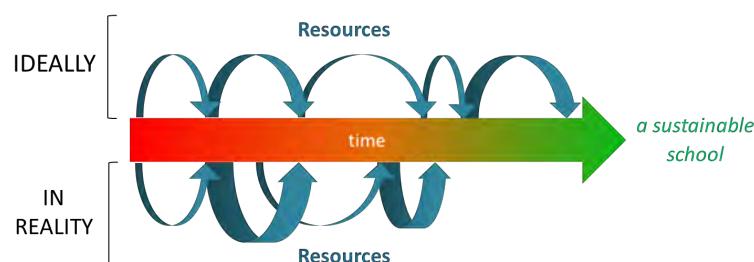


Figure 3. Renovation process towards a sustainable school, through a series of partial renovation works.

Ideal use or resources (less resources used, higher sustainability level reached)  
vs. real use of resources (more resources used, lower sustainability level reached).

The guide is developed to offer to the user:

- the opportunity to make connections between the various renovation works and also, between renovation works and objectives of well-being and impacts on environment;
- several levels of reading from a global, simplified and summarized information to an accurate technical and complete one on some specific topics.

The website focuses on school specificities. For non-specific information about sustainable architecture, links to other websites are made.

Guide content is based on:

- case studies;
- results of dynamic thermal simulation (ENERGYPLUS) on various buildings models to estimate effects of actions on the heating energy demand and on overheating problems;
- results of lighting simulations (DAYSIM) to estimate potential energy saving thanks to daylight and occupancy management.

Information given is:

- decision trees (see example in Fig.4);
- Excel tools:
  - to evaluate the impact of four renovation types on the heating energy demand (roof insulation – façade insulation – window replacement – mechanical ventilation with heat recovery installation). Calculation are based on EPBD method (simplified static thermal calculation).
  - to evaluate the impact of wall colours on light level;
  - to help in the diagnosis of the electric lighting installation.

- costs indications if possible;
  - a lot of drawings and pictures to make the content clear and understandable.

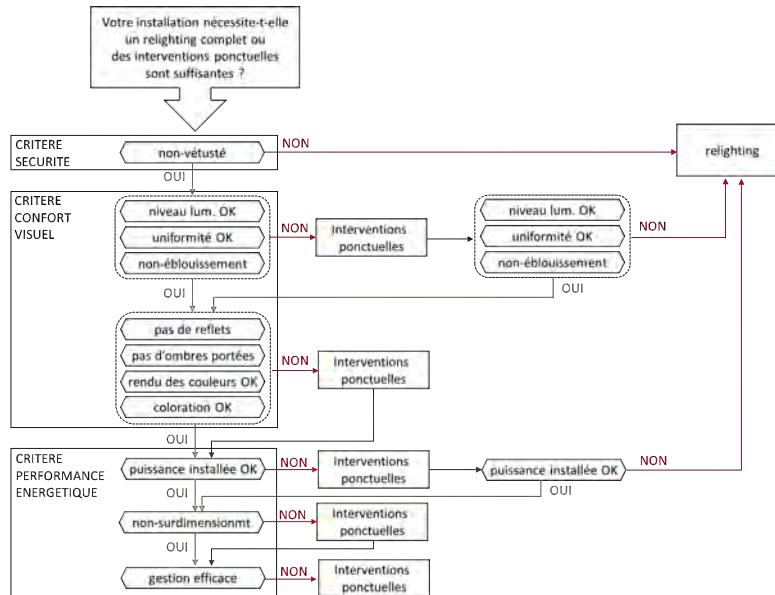


Figure 4: Example of a decision tree.

## **Structure of the online guide**

The online guide is designed to give information with two different access modes (see homepage in Fig.5):

- access by objectives (well-being or environment);
  - access by specific renovation works.



Figure 5: Homepage of the online guide

## *Access by objectives*

Objectives can be *environmental objectives* (to limit impacts of energy consumption, to limit impacts of use of building materials, to reinforce biodiversity and to limit impacts on the

water cycle) or *well-being objectives* (thermal comfort, visual comfort, respiratory comfort, acoustic comfort, connexion with nature and accessibility for all).

Each particular objective is developed from two basic questions: *Why?* And *How?*. For each objective, a *Why?* section explains why the objective is important, what are the impacts on the environment, on health and on the performance of occupants (children and teachers). The *How?* section explains how the objectives can be reached, how to evaluate the situation, what are the recommendations... The *How?* section links objectives section to renovation works section. For example, in the “How to ensure respiratory comfort” section, the visitor will find links to works such as “I want to install a ventilation system”, “I renovate windows”, “I want to do painting works”...

#### *Access by specific renovation work*

Access by specific renovation work aims at guiding the user from the renovation work he has decided to carry out (to renovate the roof, to renovate windows, to renovate the façade, to improve the heating system, to install a ventilation system, to renovate the lighting system, to limit overheating problems, to improve acoustical comfort, to improve outside spaces, to do painting work, to install solar panels, to install water saving bathroom facilities).

Each particular work is developed from the two basic questions, again: *Why?* And *How?*. The *Why?* section describes the effects that can be expected from this specific type of work, especially in the field of environmental impacts and occupants' well-being. For example, changing windows can be carried out for heating energy savings but it will also have impacts on daylight distribution, possible intensive ventilation, overheating problems... The *How?* section explains how the work can be done, what are the technical options, what has to be considered to lead to optimized design, what are the multiple criteria...

### **Conclusions**

The tool has been designed as a website to ease its spread among the potential users and to permit multiple links between topics and towards other websites. To ensure the diffusion of this web tool, several communication actions have been carried out:

- a public oral presentation of the tool in a seminar on public buildings;
- a poster in a meeting on sustainable buildings;
- a web mailing to all energy managers and municipalities;
- paper articles;
- a short TV spot.

So far, comments on the tool have been positive. Results of the communication process can be seen in the website statistics. Daily visits now turns from 20 to 40 sessions per working day. A survey is available on the homepage of the website to collect opinion of the users on the tool. Only a few answers have been collected until now but we can already say that a more user-friendly website plan, an easier access to it and a listing of available Excel tools could improve the navigation.

### **References**

Toftum, J. et al. (2015). Association between classroom ventilation mode and learning outcome in Danish schools. *Building and Environment*, 92, pp 494-503

Wargocki and Wyon (2006). The effects of classroom air temperature and outdoor air supply rate on performance of school work by children. *HVAC&R Research*, Vol.13, No.2, March 2007.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## 'Ventilate Right' – Methods of Effective Communication to New Residents

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**Abstract:** Post occupancy evaluation in housing often places emphasis on energy efficiency and the residents habits that affect this. Whilst it is straightforward to measure energy consumption and obtain the residents thermal comfort perception, the measurement and perception of ventilation is less tangible. The importance of adequate ventilation is often not communicated to residents of new housing. With buildings being constructed to be more airtight to conserve space heating energy, indoor air quality and ultimately health and wellbeing can be compromised if the planned ventilation strategies are not understood and operated by the occupant. This paper assesses methods of communicating key information to occupants, making reference to two projects undertaken in conjunction with social housing providers. One case study assesses the impact of a short film describing effective ventilation methods intended for circulation to new residents by housing providers via the internet; the other introduces the production and use of a paper based occupant guide that is unique to the home. The success of each method is discussed, concluding with an outline of innovative alternative media formats that can enhance communication with occupants to improve indoor air quality and occupant's health and wellbeing.

**Keywords:** Post occupancy evaluation, indoor air quality, short film, occupant guides, ventilation

### Introduction

Occupant understanding is a fundamental element in helping to ensure an occupied building meets its as designed energy consumption target, whilst maintaining good indoor air quality (IAQ). In a social housing context, advice to tenants regarding condensation and moisture control is not new, but there is an implied perception that ventilation advice is not so essential. In the drive to improve energy efficiency and lower dwelling carbon emissions in line with government targets, infiltration rates have been reduced. However without providing a planned, effective ventilation strategy the unintended result could be for a more hazardous indoor environment, with concurrent and significant negative long-term and undesirable impacts on public health and the building fabric. Since 2010, the Mackintosh Environmental Architecture Research Unit (MEARU) has undertaken research with residents of over 200 households in properties built to modern airtight standards in Scotland and London. This has revealed widespread evidence of poor ventilation, with bedrooms presenting a particular IAQ problem, and little awareness of potential consequences of this. Further research investigated mechanical ventilation systems and found that while these systems can deliver positive IAQ outcomes there is a risk of poor air exchange if the systems are not designed, installed and operated correctly; which was often the case. Findings from a study of housing in Scotland indicated that 83 % of mechanical extract systems were underperforming with 42 % operating below Building Regulations moisture control

requirements and 82 % of people had received no advice on ventilation (Howieson et al, 2013).

In the social housing sector where there is a relatively high turnover of tenants, simple and effective communication of good ventilation practices together with concise advice on improving energy efficient habits is of particular importance. The handover process for new residents varies significantly between social housing providers with several housing officers reporting that new tenants are handed a set of keys with little information or an introduction to their new home. Residents will often therefore apply established operational habits in new properties unaware that the new home may require a different ventilation strategy and methods of control.

The most common method of property handover in social housing involves issuing new residents with a tenant handbook. These normally consist of a series of individual manufacturers technical data sheets covering a wide range of operation and maintenance information relating to the building and its services; the residents often consider these as being too technical and are often not referred to.

Good IAQ is of particular importance and is being widely researched due to improved airtightness and the potential health impacts associated with inadequate air exchange within the home (The Royal College of Physicians, 2015). The measure of carbon dioxide ( $\text{CO}_2$ ) concentrations is frequently used as a proxy for assessment of the adequacy of ventilation air changes and the Scottish Building Standards Division (BSD) recently introduced a regulation requiring a  $\text{CO}_2$  monitor with alarm to be installed in all principal bedrooms in new housing. With the aim of alerting residents when indoor air quality is reduced to prompt action to introduce fresh air (Scottish Government, 2015). This is a step towards highlighting the importance of good IAQ however it also stresses the need for landlords to supply clear advice to their residents when occupying a new build dwelling.

### **Context of Occupant Guides**

The Scottish Technical Handbook (Domestic) provides a clause for provision of a 'quick start guide' for new homes. This is the need to inform residents of how to operate their homes for optimum efficiency, as the design intent, via a clear occupant guide (Scottish Government, 2015a). This requirement stemmed from research undertaken by MEARU for the BSD which proposed a bespoke template for such a guide in booklet form. This was trialled on new tenants in both the private and social housing sector. This research identified that whilst many residents valued the document, as it was tailored to their home, many admitted they had put the booklet into a drawer until needed (Menon and Sharpe, 2013). Many tenants admitted a 'trial and error' approach to operating heating systems, timers and ventilation systems within their home and several noted that asking a neighbour for advice seemed to be the best option, potentially perpetuating poor ventilation or energy efficiency habits. With increasingly airtight homes the importance of good ventilation practices is paramount and the occupant guides are a simple way of conveying the ventilation design intent.

Further MEARU research undertaken as part of the EPSRC funded domestic laundering project identified that moisture loads in homes can be significant and are further exacerbated by residents drying clothes on radiators in key living spaces. The project surveyed resident habits ( $n=100$ ) relative to ventilation regimes and identified that even in naturally ventilated homes, occupants often do not adjust trickle vents or open windows regularly. There was a general lack of appreciation of the importance of simple ventilation (Menon & Porteous, 2012). With increasingly sophisticated mechanical ventilation systems

including whole house mechanical ventilation with heat recovery (MVHR) becoming progressively mainstream, residents need clear and effective guidance to allow the confident operation of these for effective dwelling ventilation.

A recent survey undertaken by Ofcom, the independent regulator and competition authority for the UK communications industries, highlights that online video is becoming increasingly popular, with more than half of adults (54 %) watching television or video on a computer or mobile phone in 2015 (Ofcom, 2015). Almost a quarter (23 %) of respondents also said they had watched short video clips within the week of the survey, highlighting the popularity of video on social media. Smartphones have overtaken laptops as the most popular device for accessing web-based information, with record ownership and use transforming current communication methods. Within the social housing sector, the use of these technologies and associated applications could be developed further to allow greater access to occupant guidance and information. With this in mind, MEARU commissioned a filmmaker to produce a short information film titled 'Ventilate Right' to test the medium of film as a communication tool principally for social housing providers and their residents. The film was hosted as an online video on the website 'Vimeo' to increase accessibility and coverage.

Within that context, this paper examines alternative methods of communicating good practice for dwelling operation with a particular focus on ventilation and compares the effectiveness of a paper-based occupant guide with that of a short public advice film (hosted online) which gives helpful advice to maintain a healthy indoor environment in a simple, accessible and highly visual format.

## **Methodology**

The film, commissioned by MEARU in November 2015, was produced over a short period of time (three months from initial scriptwriting until final editing) with limited funding. The brief to the filmmaker was to produce five minutes of footage which clearly communicated the importance of maintaining good indoor IAQ levels and reducing indoor moisture loads with simple advice of how this could be achieved in both naturally and mechanically ventilated homes. The greatest challenge was to visualise the concept of 'air and moisture movement' within the house. Whilst poor ventilation can manifest itself visibly in the form of dampness and mould growth, stale and polluted air does not have such a tangible quality. In order to address this for the film, artist Rachel Duckhouse was commissioned to illustrate various moisture and potential pollutant flows for overlay animation on the film by the editorial team.

## **Film production structure**

The film was structured in such a way to address key findings of previous MEARU research with regards to moisture reduction, CO<sub>2</sub> and VOC's within the home environment. Each common resident habit and its consequences were documented and then the relevant occupant advice was integrated. Filming was undertaken at two houses in the Kingdom Housing Association development in Dunfermline, Fife, Scotland in houses which were constructed in 2013 to 2010 Building Regulations. The houses were semi-detached but each were constructed to varying thermal standards with different modes of ventilation. House 1 was Passive House certified and an MVHR system was installed. House 2 was naturally ventilated with mechanical extract fans in the kitchen and bathrooms. Residents in each house were willing for their houses to be filmed internally and assisted in demonstrating the

use of their ventilation controls as part of the filmmaking process. The film was aimed at both housing providers and residents and it was also free to access via the internet. The key challenge was to ensure that the film was not too simplistic but sufficiently technical and informative to communicate useful ventilation advice. The film content was intentionally pitched so as not to cause occupant alarm by not over stressing the health risks associated with under ventilating, instead it promoted the positive impact of a healthy indoor environment.

There is increasing evidence of a general lack of awareness of trickle vents with many occupants being unsure of where they are and when they should be used, leading to them remaining in the closed position for most of the year. Often these are inaccessible at the window head or are occluded by blinds and curtains (Sharpe et al., 2014a). The film encourages residents to locate these within their home and become familiar with opening and closing them on a regular basis. During the filmmaking the researchers noted that the living room trickle vents in House 2 had previously been taped closed by the occupant.

Potential sources of moisture within the home including showering, cooking and laundry were identified and good practice suggestions were made to minimise the impact of moisture loads with the home. The importance of opening windows was highlighted particularly for when drying clothes indoors to prevent a build-up of moisture in the home. An EPSRC funded project undertaken by MEARU in 2008 recorded the prevalence of the practice of indoor clothes drying within living spaces and bedrooms which in turn increases the moisture loads these key spaces (Menon et al., 2008).

The cleaning and maintenance of ventilation grilles and filters is critical to ensuring that the systems are working efficiently and are removing air at the rate in which they were designed. Housing Associations have varying advice and practices on the resident's level of involvement in this process but the film highlights good practice and identifies that filters should be cleaned (whether this is done by the resident themselves or for a call out to the maintenance team), the frequency of this is provided in the manufacturer information (Menon, 2015). Whilst the responsibility is on the occupant to maintain good ventilation regimes, if the means of doing this is compromised by ineffective mechanisms then their IAQ could equally be compromised. This is of particular importance in homes with MVHR systems where the resident is more reliant on this system to introduce outside air into their homes.

The film makes particular reference to houses with MVHR systems which are becoming increasingly mainstream in response to improved thermal energy requirements. MVHR systems have controls which are relatively straightforward but residents need to know when to operate 'boost' settings to increase the rate of air exchange when rapid moisture removal is required during activities such as cooking or showering. At a very basic level, residents also need reassurance that the system consumes minimal electricity and concerns regarding energy consumption should not lead to the disabling of the system.

There is increasing concern regarding high levels of volatile organic compounds (VOCs) within our indoor environments - these are off-gassed from building materials, fire retardants in soft furnishings (Figure 1) and everyday cleaning products (Liddell et al., 2008). The film aims to raise awareness of this in the context of the importance of maintaining good access to fresh air to remove any potential pollutants.

Upon completion of the film a launch event was held at the Glasgow Film Theatre (GFT) to promote the film within the social housing sector and among key policy makers and stakeholders. An invitation was sent to each Housing Association in Scotland and the event

was well attended with an engaged audience willing to provide detailed critical feedback during a question and answer session following the film screening. Subsequently the film was uploaded to 'Vimeo', a film based media website which allowed a platform for monitoring views but also allowed organisations to link to it on their own websites.



Figure 1 Potential VOC release from fire retardants in soft furnishings

In order to gain further feedback, one year later (February 2017), a follow up postal survey was sent to housing officers within Housing Associations across Scotland to ascertain whether they were aware of the film; whether they would consider using it as part of their handover process and to gain further feedback regarding the content of the film itself. In addition to this, the survey asked social landlords probing questions regarding their current handover procedures and whether these could be improved by the use of enhanced digital media communication tools.

#### **Data-Feedback from housing providers**

For the purposes of this paper feedback from the film is centred on a short survey questionnaire which was distributed by postal service to Housing Associations ( $n=60$ ) across West Central Scotland. Whilst the return rate was only 25 %, the information returned was significantly detailed and many respondents expressed a willingness to host the film on their website and engage in the development of further occupant guidance via web-based communication tools.

When asked whether it is standard procedure within their organisation for a housing officer to accompany a new resident when they first move in 60 % agreed this to be the case indicating that 40 % of residents are given keys and require to understand the workings of the home themselves. 67 % of respondents confirmed that their Housing Association issue new tenants with a handbook relative to their property however of this figure only 20 % could confirm that this included technical guidance on the use and maintenance of the mechanical ventilation systems (including both extract fans and MVHR systems).

It is evident from feedback that a lot of practical advice is delivered verbally by housing officers and maintenance departments with 73 % of Housing Associations confirming that advice regarding moisture control in the home is provided to residents. Whilst this is likely to be beneficial to the occupants, a more formal documented process which could allow residents to re-visit it once they have settled into their new dwelling or allow those family members not present at the handover meeting to benefit from the information.

Housing Associations certainly have the resource in place to deal with any residents having difficulty operating mechanical ventilation systems, 73 % identified that a maintenance officer, technical inspector or estates team member would deal with such problems however there seemed to be less clarity ascertaining who was responsible for changing filters on mechanical ventilation systems with only 53 % of respondents noting that they undertake this scope of works. Of those 53 %, only 25 % would only change a filter if a problem was identified by a maintenance officer thereby implying that filters were not changed on a regular basis. 67 % of respondents noted that their tenants were expected to clean ventilation grilles themselves yet little or no advice was contained in the tenant handbook of how to go about this or how to determine whether the fan itself was indeed performing as it was designed to.

Of the Housing Associations surveyed, only 33 % noted that they currently host occupant guidance on their website with most commenting that their primary method of communication with residents is through a resident newsletter or e-bulletin. However, in response to a question enquiring whether they would consider hosting information regarding ventilation and IAQ on their own website, 100 % answered positively.

The questionnaire progressed with a request for the respondent to view the film online at <https://vimeo.com/163384704> and provide feedback on the content, duration, style and target audience. 67 % of respondents viewed the film and feedback was varied and sometimes contradictory - some reported the film was too long and detailed whilst others noted it could have benefited from more discussions of the impact of poor IAQ and more examples of the potential causes. 60 % however reported that the film provided simple and effective advice and was pitched correctly for its target audience. When asked if they thought that a film is a better way of telling residents about the importance of ventilation than a technical manual, 100 % of respondents agreed with several noting that paper-based documents often get misplaced in the home therefore a digital format was deemed more beneficial.

The feedback concluded with an open question asking their opinion of the best method of advising tenants how to ventilate homes. The majority of respondents noted that the 'face to face' approach was favoured as it is not only the most effective method of locating and demonstrating controls but it also established a relationship between the housing officer and the resident which is key to any Housing Association. Several respondents appreciated that coordination of this handover was a fairly labour intensive process. It was also noted anecdotally that given the high percentage of non-English speaking residents within the social housing sector, highly visual formats of communication are much more beneficial. One respondent suggested a digital format which could be distributed via mobile technology may be relevant in the coming years given the prevalence and accessibility of social media across all social sectors.

In addition to the survey data, the feedback on the effectiveness of the film was garnered at a film launch hosted at the GFT which included a screening of the film and then discussion panel, feedback from industry. Some feedback suggested that the film was not technical enough whilst others disagreed and highlighted that it hit its target audience. Several Housing Associations present at the event requested DVD formats of the film so they could be used as a training video to their housing officers. On the day of the film launch the BBC covered the story and following this the subject of IAQ became a feature on BBC Breakfast on prime-time UK television. The web-based BBC news article provided a link to the film and the number of views was tracked which since the film was launched it has been

viewed nearly 2,000 times. This has also prompted several Housing Associations and other organisations to host the film on their respective websites.

## **Discussion**

The data clearly demonstrates that there is currently no standard handover procedure for new tenants in social housing and whilst a tenant handbook is available, the content and method of issue varies significantly. It is evident that whilst many housing providers have housing officers who show a tenant around the house demonstrating the key features of the home others simply give a set of keys to new tenants and they are left to a process of 'trial and error' or forced to consult overly complicated technical manuals. Respondents anecdotally indicated that new residents are too overloaded with information on the day they move in and often the maintenance officer is required to deal with any problems which arise at a later date. This highlights that a more accessible medium which could be re-visited by members of the same dwelling may be beneficial, as such, the online film can be hosted on landlords website or on social media and accessed when required. Given the statistics regarding the increasingly widespread use of smartphones using this as a tool to provide advice to residents seems to be advantageous.

In comparison to the effectiveness of the paper based logbook, a film advising residents how to use their home is clearly an effective tool. Issues relating to residents ability to read plans to locate systems and controls are removed and whilst the film based advice guide may not be particular to their home, residents can instantly make visual connections to similar features in their homes and where they are located. Home log book providers have been developing digital platforms to provide digital storage for manuals and technical brochures which is certainly a step towards addressing previous resident feedback which suggested that keeping a manual in the drawer is the norm.

## **Conclusion**

This paper highlights the potential demand for further public advice films for occupants with regard to the changes that require active ventilation to balance energy efficiency and indoor air quality. The 'Ventilate Right' film has succeeded in its aim to raise awareness of the importance of ventilation for general living environments. It has been an excellent pilot study to enhance and further develop occupant guidance using a variety of media which can be potentially integrated with the ever increasing popularity of mobile technologies. It is also important to note in the context of the building performance gap between designed performance and actual recorded data that whilst occupant behaviour is an important factor there is an understanding that the ventilation systems in the house should be installed correctly, are well maintained, are simple to operate in the first instance and the planned ventilation strategy must be effectively communicated. A resident can only expect to regulate their indoor environment if these systems are in place and are performing as designed. The consumer market for indoor air monitors and alerts synchronised with an application on mobile technology is in its infancy but as the awareness of healthy indoor environments increases the popularity of such devices will no doubt develop and has the potential to be combined with occupant guidance for dwelling operation.

Housing Associations are currently addressing occupant guidance with varying degrees of success. Ultimately good ventilation advice is critical to social landlords as they have a duty of care to their residents to provide indoor environments which are not only thermally efficient but also healthy.

Housing providers which have developed new build housing stock since the October 2016 revision to the Scottish Building Regulations will require to develop a body of practical advice and tips for residents regarding to help with maintaining good IAQ particularly in light of the requirement for CO<sub>2</sub> monitors in principal bedrooms, which will no doubt trigger a new realm of queries from residents.

To conclude, more research is needed in this area with enhanced engagement with housing providers to develop tools to help them deliver occupant advice effectively and consistently. Further research to test the effectiveness of the occupant guidance whether in paper based format or using media such as short film could be undertaken through a programme of environmental monitoring before and after the guidance has been issued – this would allow an assessment of the impact of occupants habits. This research together with the potential use of mobile smartphone technologies as a platform for resident engagement are exciting propositions.

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### References

- Howieson, S., Sharpe, T., & Farren, P., (2013). Building tight – ventilating right? How are new air tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology*, 35(5), 475–487. doi:10.1177/0143624413510307
- Liddell, H., Gilbert, J., Halliday, S., (2008). Design and Detailing for Toxic Chemical Reduction in Buildings. Available online: <http://seda.uk.net/assets/files/guides/dfcrb.pdf> (accessed on 25 January 2016).
- Menon, R., (2015). Multiple Occupancy Residential Accommodation-Ensuring Good Indoor Environments. European Network for Housing Research 27<sup>th</sup> International Conference, July 2015, Lisbon.
- Menon, R., Porteous, C., (2012). Design Guide: Healthy Low Energy Home Laundering. Available online: [http://www.gsa.ac.uk/media/486640/mearu\\_laundry\\_design\\_guide.pdf](http://www.gsa.ac.uk/media/486640/mearu_laundry_design_guide.pdf) (accessed on 25 January 2016).
- Menon, R., Porteous, C., and Sharpe, T., (2008). Environmental Impact of Domestic Laundering EPSRC (EP/G00028X/1).
- Menon, R., Sharpe, T., (2013). The Benefits of Occupant User Guides in Achieving Low Energy Homes, European Network of Housing Researchers Conference (ENHR) July 2013, Taragona, Spain.
- Ofcom, (2015). Communications Marketing report, Adults' media use and attitudes.
- The Royal College of Physicians (RCP) and the Royal College of Paediatrics and Child Health (RCPCH), (2015). Every Breath We Take: the lifelong impact of air pollution.
- Sharpe, T., McQuillan, J., Howieson, S., Farren, P., & Tuohy, P., (2014a). Research project to investigate occupier influence on indoor air quality in dwellings. Livingston: Local Government and Communities. Retrieved from <http://www.gov.scot/Resource/0046/00460968.pdf>
- Scottish Government, (2015). Scottish Building Regulations: Technical Handbook, Domestic. Section 6 Energy. Available online: <http://www.gov.scot/Resource/0047/00478112.pdf> (accessed on 27 March 2017).
- Scottish Government, (2015a). Scottish Building Regulations: Technical Handbook, Domestic. Section 7 Sustainability. Available online: <http://www.gov.scot/Resource/0047/00478112.pdf> (accessed on 27 March 2017).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## How Can the Combination of BREEAM and Soft Landings Successfully Deliver a Low Energy, Comfortable Building?

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**Abstract:** The performance gap is an industry-wide challenge, disreputably known to all building practitioners. Design teams spend a good portion of the project timeline designing a building that often fails to deliver the project targets without them even being informed. This seems unjustifiable when there are many tools available for advanced performance modelling, lifecycle sustainability strategizing, and stakeholder engagement, to plan, review, and meet the design specification. This paper presents a practical lifecycle guide, based on building phases, to design and deliver energy-efficient buildings with minimized performance gap with respect to energy use and occupant satisfaction. This guide offers a holistic approach for realizing the highest potential of BREEAM and Soft Landings (SL) to address the key contributing issues of performance gap and the inevitable future circumstances. It draws on the commonly used sustainability certification schemes, including BREEAM, NABERS, LEED, Living Building Challenge; as well as, Post Occupancy Evaluation (POE) procedures and Soft Landings (SL) framework. Furthermore, this study draws on the specific lessons learned from two major projects at the Heriot-Watt University Campus that utilized BREEAM and SL in their design and delivery.

**Keywords:** Performance Gap, Practical Lifecycle Guide, Soft Landings, BREEAM, POE

### Introduction

Increased energy use and diminished occupant satisfaction is known as performance gap, which is considered to have three underlying causes: (1) faults in building envelope and systems, for instance thermal bridging or low airtightness; (2) building users' influence, such as erroneous operation of the systems; and (3) inaccurate predictions including wrong assumptions and standards concerning internal and external conditions, i.e. use behaviour and pattern and weather conditions. (Menezes et al., 2012; Olivia and Christopher, 2015).

In many projects, energy modelling is performed to inform design-decisions and produce Energy Performance Certificates (EPCs) for compliance testing and building certification. EPCs are compared against Display Energy Certificates (DECs), which are for public display and are based on actual energy use after the twelve-month liability period (de Wilde, 2014). Practitioners do not recognize EPCs as reliable measures of building performance as they only consider heating and cooling loads, whereas DECs present measured values and include unregulated energy sources such as plug loads (de Wilde, 2014; Palmer et al., 2016).

Traditionally building use surveying was only performed for investigation of serious malfunctions or for research aims in a pilot or exemplary building. With the industry

embracing the concept of continuous improvement, designers and contractors are more interested in extended aftercare and building performance in-use (Olivia and Christopher, 2015; Preiser, 1995), as there are many project-specific as well as long-term industry benefits. Empirical data shows that the main barrier to studying the building performance in-use has been liability issues and financial incentive conflicts for investment beneficiaries of Post-Occupancy Evaluation (POE). These barriers are largely overcome by the industry interest in the lessons-learned and the consequential cost savings, besides, revised contractual agreements and procurement methods (Olivia and Christopher, 2015). Shi et al. suggest POE as a solution to the cost and functional effectiveness trade-off, which is a conflict between the developer/client and the end users (Shi et al., 2016). Project capital budget highly influences the ability of a project to perform POE (BSRIA, 2014). Low budgeted projects can tend to focus on building to the current regulations at the minimum capital cost possible (Gul and Menzies, 2012). Fortunately, technological advancement of smart monitoring systems, such as sensors, sub-meters, and building management systems (BMS) has made monitoring and evaluating procedures more affordable for most project sizes.

Typically, about 90% of company expenditure is on staff salaries and benefits, compared with approximately 1% energy use costs (Browning 2012; WGBC 2014). This shows the extent of financial benefits of the smallest increase in productivity of the building users and the importance of sympathetic operation of buildings and reliable evaluation of occupants' satisfaction, health, and wellbeing (Pottage and Jeffrey, 2016). Systematic performance evaluation throughout an asset's lifespan is essential to effectively and efficiently design and deliver buildings that meet the needs of stakeholders throughout their lifetime, or in other words are 'future-proofed' (Love et al., 2015).

In the UK, BREEAM is a well-established tool to incorporate low energy and sustainable solutions from the early design stage. BREEAM rates the environmental impacts of a new construction project at two stages: Interim Design Stage based on the Scheme or Detailed Design evidence (RIBA stage 3); and Post Construction Stage based on 'as-built' information following practical completion of building works (RIBA stage 5) (BRE Global LTD, 2014). Therefore, it is criticized for not holding projects accountable by certification based on actual use evidence (Tuohy and Murphy, 2014). Zero Carbon Hub recently advised that future standards should be linked to actual performance in order to close the performance gap (Zero Carbon Hub, 2014). NABERS, the Australian sustainability rating scheme that is based on actual annual energy use, has shown more successful results in reducing performance gap compared to BREEAM and LEED (Tuohy and Murphy, 2014)

Soft Landings (SL) is a strategy to ensure smooth hand-over and optimize operational performance through stakeholder engagement, systematic monitoring, and POE. Coordination among the design and construction team and all the significant project stakeholders is among the main pillars of SL to effectively achieve the design objectives (Li et al., 2011). The Soft Landings Framework (SLF) is a joint initiative between BSRIA and the Usable Buildings Trust (UBT), first published in 2009 and updated in 2014 to align with the RIBA 2013 work stages (BSRIA, 2014). Government Soft Landings (GSL) is a policy document for all centrally-funded projects as part of the public sector adopting Building Information Modelling (BIM) (BIM-Task-Group, 2013; BSRIA, 2014). SLF and GSL are aligned as they target reducing performance gap through POE in extended period and contract commitment beyond the typical defect liability period and closer integration of the design, construction, and operating parties involved (BIM-Task-Group, 2013). Both frameworks use structured familiarization workshops for handover; and walkthrough, surveys, and interviews for in-use

feedback collection to identify performance gap and teething issues (Pottage and Jeffrey, 2016). Yet, GSL is more prescriptive regarding incremental checks for BIM adoption and provides a mechanism to monitor costs. SLF is less strict about project objectives and focuses on increased collaboration and awareness of outcomes through stakeholder workshops and design reviews following the program defined by the SL Champion. Another main difference is that GSL starts at RIBA stage 0 or 1, whereas the SFL sets targets at stage 2 (BSRIA, 2014).

SL and BREEAM are a promising combination of lifecycle-oriented tools to future-proof buildings (Georgiadou et al., 2012). This paper presents a lifecycle plan of work for reducing performance gap through successful planning and implementation of BREEAM and SL into a project to achieve a low-energy, comfortable building. This action plan is prepared according to the RIBA Plan of Work 2013 and the UK Government Digital Plan of Work (BIM-Task-Group, 2013; HUNT, 2016; RIBA, 2013). All the recommendations are based on the reported lessons learned in white papers and academic publications concerning performance gap, POE, green building schemes, and BREEAM and SL documents; as well as, the knowledge collected from two actual case-studies at Heriot-Watt University campus that were procured and delivered using BREEAM and SL. Table 1 offers a summary of the guide and the organization of this paper.

Table 1. Summary of the practical lifecycle guide presented in the following paper sections.

Lifecycle Phase	Plan of Work	
<u>Strategy and Brief</u> (RIBA stage 0-1)	i. Explore regulatory and project specific objectives ii. Plan and set targets	
<u>Concept to Detailed Design</u> (RIBA stage 2-3)	i. Test objectives ii. Design and Model iii. Test modelled performance	BREEAM
<u>Tender Design and Construction</u> (RIBA stage 4-5)	i. Evaluate buildability ii. Construct	
<u>Handover and In-Use</u> (RIBA stage 6-7)	i. Familiarization Workshops ii. Fixing metering and sub-metering readings versus BMS iii. Identifying building defects and fine-tuning iv. Occupant Satisfaction Surveys after a year of occupation	

### Strategy and Brief (RIBA stage 0-1)

The transition from construction to occupation should be considered throughout the development of a project. An early adoption allows for allocation of an appropriate budget, conservative and prescriptive contract appointments, and inclusion of provisions in the briefing documents. In the first stages of project development, the client shall review the government and local regulations, feedback from similar projects and establish the project targets for the Project Brief. The brief shall include quantifiable project aspirations regarding: (1) project business case and schedule covering project capital and operational budget; (2) performance targets regarding: a) building functionality and effectiveness in operation and maintenance, b) commissioning plan, metering and monitoring strategy, and training and handover requirements; (3) sustainability aspirations: a) environmental, including: energy and water consumption, carbon emissions, and waste, b) social, including: occupier comfort, locally sourcing of materials and workforce, consultation and end-user involvement; (4) other requirement discovered through feasibility studies and site inspection (BIM-Task-Group, 2013; BSRIA, 2014; RIBA, 2013). The brief should be interrogated until excellence.

Along with the conventional design team, the following members shall be appointed from the outset: (1) a sustainability champion such as a BREEAM consultant and a SL champion to supervise the appropriate strategies (BSRIA, 2014); (2) construction team to involve them in review meetings to provide feedback on build concerns (Zero Carbon Hub, 2014); (3) facility managers or FM advisors to assist with ensuring that the design specifications are aligned with final users' needs and requirements (BSRIA, 2014). BREEAM encourages consultation with the end-users and the relevant third-party stakeholders prior to completion of the Concept stage (RIBA stage 2).

The two considered case studies had a rushed brief development, whereby the binding documents only mentioned BREEAM and SL, but did not impose any BREEAM target or SL procedure in detail. This allows the stakeholders to revert to the traditional performance indicators and familiar, traditional practices when facing budget or time schedule overrun.

### **BREEAM and Synergies with SL**

While minimized energy consumption and energy security are important factors in building future-proofing, benefits related to building and building users are claimed to outweigh energy cost savings considerably (WGBC, 2013). Although green building certification schemes consider all these beneficial factors, investment decisions are commonly founded on only energy and associated operational cost savings, mainly because the other benefits are too unpredictable to shape business cases (Pottage and Jeffrey, 2016). Table 2 presents the BREEAM credits that are aligned with the SL framework, along with their contribution to the total score for a new, fully-fitted BREEAM 2014 construction project. These credits contribute 7.66% to the overall score and have essential impact on reducing the performance gap through energy monitoring, user engagement, or occupant satisfaction.

Performing POE one year after initial occupation scores 1 point for the project and delivering an enhanced, quarterly POE over the first three years of occupation qualifies for 1 exemplary-level point (given that the POE findings are disseminated) (BRE Global LTD, 2014).

Table 2. BREEAM credits recommended by and are in line with the SL framework.

BREEAM Credit & Section	Credit Summary	X	Y	Z
Management	01 Project Brief and Design Stakeholder consultation: project delivery and relevant third parties.	2	0.57%	UE
	Commissioning and testing schedule and responsibilities	1		EM
	Commissioning building services	1		UE
	Commissioning building fabric	1		OS
	Handover (Building User Guide/Training schedules)	1		
	Aftercare Support to the occupiers	2		EM
	Seasonal Commissioning over a minimum 12 month period	1		UE
	POE one year after initial occupation and to disseminate the findings	1		OS
	Quarterly enhanced-POE over the first 3 years of occupation	+1		
			1%	
Energy	02 Energy Monitoring (Sub-metering) Major energy consuming systems	1	0.48%	EM
	High energy load and tenancy areas	1		

<sup>1</sup> X: Points achieved by abiding by the requirements of the credit

<sup>2</sup> Y: Section weighting (each point's contribution to the total score) for a new, fully fitted BREEAM 2014 project

<sup>3</sup> Z: Reducing performance gap by: EM=Energy Monitoring; UE=User Engagement; OS=Occupant Satisfaction

In addition to the credits presented in Table 1, BREEAM largely focuses on improving occupants experience and satisfaction by prioritizing their health and wellbeing through: appropriate glare control, view out, daylighting, and lighting levels; indoor air quality and thermal comfort studies, and thermal control zoning; improved acoustic performance and safety and security; and site selection based on good public transport linkage, proximity to essential amenities, and cyclist facilities.

Moreover, the Energy section of the BREEAM manual encourages energy efficient solutions through the following strategies: use of energy simulation methods to predict and reduce operational energy use and carbon emissions; specification of energy efficient lighting and equipment; provision of adequate drying space; analysis for adoption of passive design solutions and low/zero carbon energy sources. Similarly, the Materials section aims to raise awareness about green building materials that assist with emission reduction, higher asset value, reduced operating costs, and enhanced worker productivity due to healthier indoor environment.

### **Concept to Detailed Design (RIBA stage 2-3)**

During the concept development the project brief is revised to a final version that reflects specific requirements for design, construction, handover, and operation deliveries. It should include: (1) measurable targets and (2) strategies for assessment. In addition to the conventional design documents and specification, it is recommended to have a plan and an expenditure budget for operation management, commissioning, training and handover, and aftercare support. Budget plans must be reviewed and design development and value-engineering must be monitored to ensure design targets can be achieved. Whole life costing shall be performed at this stage. Clash detection must be performed throughout the design process to minimize services and fabric integration troubles on construction site

### **Tender Design and Construction (RIBA stage 4-5)**

At this stage the design and digital models are translated into a constructed building. From RIBA stage 4, the contractor is actively involved in document preparation. The contractor shall allow for the participation of relevant subcontractors in design reviews, and record and act on access, commissioning and potential maintenance risks identified, where appropriate (BIM-Task-Group, 2013). Requesting inclusion of all sub-contractors on a pre-tender list will allow comparison on issues such as energy related skills (Zero Carbon Hub, 2014).

The Technical Design documents including architectural, structural and building services information, specialist subcontractor design and specifications are prepared. Regular reviews are recommended to ensure that the set performance and cost targets are still within horizon and accurately strategized. Suppliers and facility management are employed to review the operation management plan and expenditure budget. Lack of adequate quality assurance on construction site has resulted in aspects of construction related to the performance of the completed building not being prioritised. The considered case-studies have also suffered from lack of monitoring and quality assurance during construction. Weak site energy performance management results in improper insulation fitting, incorrect services installation, and poor details construction (Zero Carbon Hub, 2014). Regrettably, SL does not include monitoring during construction and the extent of influence of project size, construction type, or contractual approach on this issue, is unclear. After construction is completed, taking thermographic images of completed buildings can assist with detecting problems with construction details (Palmer et al., 2016).

It is essential to plan for commissioning before handover along with the operational team to optimise the performance of the energy systems (BIM-Task-Group, 2013). At this stage the asset register and asset operation and maintenance manuals are prepared. Testing and commissioning are required for practical completion and allow clients the mandate to hold completion. It is recommended to hire independent commission specialists to police the M&E testing. Calibration of controls, metering, and complex mechanical or electrical systems can become challenging. Simpler systems and controls have proven to be more user-friendly and efficient (Palmer et al., 2016). The case-studies' users found inconsistent selection of controls within the building spaces confusing and inconvenience. BMS is a convenient centrally controlled method and can over-ride controls. However, it has proven to be complicated to regulate for commissioners and operate for occupants and facility managers. Therefore, similar to the case-studies, projects repetitively report BMS conflict with other system controls, which leads to confusion and wasteful energy use (Palmer et al., 2016).

### **Handover and In-Use (RIBA stage 6-7)**

Even though, RIBA stage 6 and 7 are named as two separate phases, namely, "handover and close out" and "operations and end of life"; SL blurs the line between these two phases by adding 3 to 4 years of building performance evaluation to reduce performance gap. The liability period is still at the end of the first year of occupancy, which is why it is essential to financially incentivize and contractually guarantee continuation in the following years.

Zero Carbon Hub suggests focusing on robust verification of energy performance, for example by Building Control Bodies or warranty providers. To reduce performance gap, it is essential to allocate sufficient time and financial incentives for a systematic and structured quality assurance process (Zero Carbon Hub, 2014). It is recommended to evaluate: (1) In-use performance for three years including meter and sub-meter recording, corrective actions and fine-tuning; (2) The desired against the achieved environmental performance goals; (3) Actual capital out-turn cost and operational costs for a period of three years (POE).

Performance monitoring and evaluation results identifying the areas where performance has required additional work beyond that envisioned (BIM-Task-Group, 2013). During the handover period, familiarization workshops shall be arranged for the facility management team covering the change control, metering, and monitoring systems, whereby the required operational skills are provided and training is documented for future reference.

There are various POE methods to choose from and it would always worth looking at a hybrid of methods or adapting one method to the scope and needs of the case without compromising the possibility of benchmarking against the available datasets. It is for the sake of benchmarking that generally applicable techniques are favoured by some prominent authors such as Bordass and Leaman. These methods should be broadly applicable, holistic, and robust, besides being free, simple, and quick to implement (Bordass and Leaman, 2005). For instance, the Building Use Studies (BUS) occupant survey and reporting method has a rich database of POE results that allows for benchmarking in several countries including the UK (The Usable Buildings Trust, 2007). Another benefit of this method is the quick data analysis performed by the UBT, which is essential to accelerate corrective, follow-up actions.

Because the POE process involves building managers and users and requires a considerable amount of time and other resources, it is essential to perform a pragmatic research and investigate only what is relevant. The selection should be based on the study objectives, depth, and nature, the reporting audience, and the available resources (Olivia and Christopher, 2015). These performance evaluations shall include building fabric tests such as

airtightness testing and thermographic survey, commissioning of building services and controls.

SL suggest evaluating building performance using three methods: (1) Regular inspection walkthroughs that check the building's operation looking for any emerging problems or wasteful operational practices; (2) Continuous survey of the energy use breakdown by type of consumption for example, heating, air conditioning, as well as space zones through energy sub-meters; (3) Assessment of occupant satisfaction using surveys and interviews, ideally one year after building occupation to cover at least one seasonal cycle (Agha-Hossein et al., 2015; Palmer et al., 2016)

## Discussions

Knowledge turnover is crucial for a system to evolve sustainably. In a stable system, such as the construction industry, knowledge turnover is abridged and new alterations are rarely continued. In such systems, it is recommended to start a variation from the less established parts, where faster knowledge conveying occurs and is appreciated (Shepherd, 2004). Therefore in order to transit the industry to where it can benefit from full digital design and delivery and allow for continuous improvement, we shall focus on extended aftercare and stakeholders' engagement that are not established practices and systematically collect data, record the lessons-learned and best-practice, and combine data collection and modelling verification for better forecasting.

Even though BIM is recommended as the catalyst to future-proof buildings (Love et al., 2015), the results of the recent Construction Manager BIM survey revealed stagnation in implementation since the mandate for adoption in publicly funded projects a year ago. This survey concludes that clients are not certain what to specify and how BIM should be applied per contract or procurement type; thus, clients see BIM as additional expense with no benefits (Chevin, 2017). Hence, until BIM develops to its full utility, the construction industry requires compensating tools that assist with future-proofing buildings within its current capacity and stable structure and smooth the transition to the digitalized industry.

The sources of performance gap as described in the introductory section can be managed through the SL steps described above that encompass a process of stakeholder involvement and POE and result in manifold of benefits at two levels:

- Project Specific: improved building performance and reduced operative costs and performance gap, achieved by: (1) fine-tuning; (2) proper use of building systems
- Continuous Improvement through developing a wider knowledge base, achieved by: (1) long-term competitive advantage; (2) informed policy developments; (3) intra-agency feed forward of guidance criteria; (4) improved services by designers, builders, facility managers; (5) more accurate simulation assumptions; (6) establishing baselines based on stages of building life cycle (Menezes et al., 2012; Olivia and Christopher, 2015; Preiser, 1995).

## Conclusions

BREEAM and SL rely on the current industry expertise and structure and do not require complex training or tools. They provide a common platform for dialogue and collective action and continuous improvement. Yet, a series of important steps must be followed to implement these frameworks successfully with minimum human and financial resources; to benefit from their synergies; and to ensure continuance. Accordingly, this paper presents a holistic plan of action for successfully adopting BREEAM and SL at different stages of a building lifetime.

This practical guide assists with effectively reducing the performance gap and designing and delivering low-energy and comfortable buildings through highlighting the underlying reasons for performance gap and recommending implementable actions at each stage of a project lifetime for a successful project target delivery.

Given that the two case-studies considered are at the end of their first year of occupancy and still in the process of fine-tuning, disclosure of their SL information and results were not yet possible. However, some of the focal lessons learned are discussed.

## References

- Agha-Hossein M, Birchall S and Vatal S (2015) *Building Performance Evaluation in Non-domestic Buildings – A guide to effective learning*.
- BIM-Task-Group (2013) *Government Soft Landings*.
- Bordass B and Leaman A (2005) Making feedback and post-occupancy evaluation routine 1: A portfolio of feedback techniques. *Building Research & Information* 33(4): 347–352.
- BRE Global LTD (2014) *BREEAM New Construction - Non-Domestic Buildings - Technical Manual*.
- BSRIA (2014) BSRIA Soft Landings Framework Guidance Documents. Available from: <https://www.bsria.co.uk/services/design/soft-landings/free-guidance/> (accessed 4 April 2017).
- Chevin D (2017) Clients still not buying into BIM, reveals survey. *BIM+*. Available from: <http://www.bimplus.co.uk/news/clie6nts-still-n7ot-buyin8g-bim-reveals-cm-survey/> (accessed 4 April 2017).
- de Wilde P (2014) The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction* 41: 40–49.
- Georgiadou MC, Hacking T and Guthrie P (2012) A conceptual framework for future-proofing the energy performance of buildings. *Energy Policy* 47: 145–155.
- Gul MS and Menzies GF (2012) Designing domestic buildings for future summers: Attitudes and opinions of building professionals. *Energy Policy* 45: 752–761.
- HUNT S (2016) RIBA STAGES AND BIM: YOU CAN'T PLAY A NEW GAME WITH OLD RULES. *BIMPlus.co.uk*, London.
- Li YY, Chen P-H, Chew DAS, et al. (2011) Critical Project Management Factors of AEC Firms for Delivering Green Building Projects in Singapore. *Journal of Construction Engineering and Management* 137(12): 1153–1163.
- Love PED, Liu J, Matthews J, et al. (2015) Future proofing PPPs: Life-cycle performance measurement and Building Information Modelling. *Automation in Construction* 56: 26–35.
- Menezes AC, Cripps A, Bouchlaghem D, et al. (2012) Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy* 97: 355–364.
- Olivia G-S and Christopher TA (2015) In-use monitoring of buildings: An overview and classification of evaluation methods. *Energy and Buildings* 86: 176–189.
- Palmer J, Terry N and Armitage P (2016) *Building Performance Evaluation Programme: Findings from non-domestic projects*.
- Pottage C and Jeffrey H (2016) A Case Study of the Metrics of Capturing the 'Green' Improvements on a New Office Building. In: *Sustainable Ecological Engineering Design*, Cham: Springer International Publishing, pp. 127–147.
- Preiser WFE (1995) Post-occupancy evaluation: how to make buildings work better. *Facilities*, MCB UP Ltd 13(11): 19–28.
- RIBA (2013) *RIBA Plan of Work 2013*.
- Shepherd J (2004) What is the Digital Era? In: *Social and Economic Transformation in the Digital Era*, IGI Global, pp. 1–18.
- Shi Q, Yan Y, Zuo J, et al. (2016) Objective conflicts in green buildings projects: A critical analysis. *Building and Environment* 96: 107–117.
- The Usable Buildings Trust (2007). Available from: <http://usablebuildings.co.uk/> (accessed 17 April 2017).
- Tuohy PG and Murphy GB (2014) Closing the gap in building performance: learning from BIM benchmark industries. *Architectural Science Review*, Taylor & Francis 58(1): 47–56.
- WGBC (2013) *The Business Case for Green Building. A Review of the Costs and Benefits for Developers, Investors and Occupants*.
- Zero Carbon Hub (2014) *Closing the gap between design & as-built performance - Evidence Review Report*. London.



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*Design to Thrive*

## Bridging the gap: A framework for a robust sustainable design process

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**Abstract:** There is an ongoing deficiency in the application of sustainability theory through design by many construction professionals including architects. While sustainability knowledge has grown, importance should not be placed solely on its existence, but rather improving knowledge through its application and adoption in order to lessen performance gaps. While there are existing techniques to assist in meeting these challenges (e.g. design process guidance, environmental assessment guidance and software tools) research conducted by the author through a design charrette revealed limitations to this guidance in its current form. These findings indicated that of the guidance available, an integrated and informed design process has the most potential to be successfully developed to more effectively implement well-performing sustainable design. The author recommends a framework for the form, content and application this sustainable design process guidance should take, and suggests it would help give a bottom-up approach to how sustainability should be defined and implemented in practice; helping to move the current design process paradigm towards a sustainable design process one. Such guidance would be a practical tool that is universally accessible and capable of responding to changes in context in order to enable practitioners to create and deliver buildings that perform as intended.

**Keywords:** Sustainable design process, sustainable design guidance, inexperienced sustainable designers, performance gap, sustainability implementation

### Introduction

Building professionals require the knowledge, skills and tools to understand and implement sustainable design in practice; not solely to respond to a top-down legislative agenda but additionally to improve the user experience of buildings and respond to sustainability issues from the bottom-up. Architects are key professionals within this process as the building consultant with the earliest influence on the design, and the need for architects to possess the sustainable design skills to support this role is crucial for future sustainable development. Whilst there appears to be a reasonable understanding of concepts and theory surrounding sustainable design currently within design practice, there is an ongoing deficiency in the *adoption and application* of this theory through design. This deficiency manifests itself in continued high levels of building energy use and oil dependency (Eurostat, 2016), in building performance gaps (Bordass and Leaman, 2013), in the lack of sustainable buildings which go beyond tepid 'greening' (Irish Green Building Council, 2012) and in the lack of robust sustainability confidence in architects (NBS, 2012).

This paper suggests therefore that importance should not be placed solely on architects gaining possession of sustainability knowledge, but rather improving their skills in the *application and adoption* of it within the design process. The focus of this paper is therefore the review of available sustainable design guidance in the form of processes,

methods or tools and the effective implementation of same by architects. It examines to what extent guidance might better support a more successful realisation of sustainable design. The focus stage is early stage design guidance - as these early stages are most influential, and the focus consultant is inexperienced sustainable design architects in Ireland who are interested in these issues but unclear how and when to implement them.

Therefore, this paper seeks to firstly briefly summarise through literature review what current guidance is available. These broad findings are further discussed and verified by the findings of a design charrette conducted by the author which evaluated how current guidance is being utilised, and offers suggestions on how sustainable design guidance should be offered in the future in terms of a guidance framework which would enable architects to not only develop sustainable design skills and ability but to implement same.

### **Existing Design Guidance**

A literature review was undertaken to examine the effectiveness of current sustainable design guidance in the Irish early design context. There is currently sustainable design guidance available in the form of processes, (e.g. RIBA overlay) [environmental assessment] methods (e.g. LEED) and tools (software and manual). This guidance is an attempt to give some structure to a problem and to organise decision making sequences to help reduce design waste (Magent et al., 2009).

Current design **process** guidance does not address definition, realisation or sequencing of sustainable design ideas and standards. Instead, it offers a design process in which sustainability, where pursued, is added as an additional aspect to existing linear processes, manifesting in a 'DESIGN PROCESS plus SUSTAINABILITY' whereas what is called for is a SUSTAINABLE DESIGN PROCESS which incorporates sustainability within the design process. Current **method** guidance helps to set the [aspirational] goals of sustainable design – the definition - but not the means to achieve them - the realisation and sequencing is not addressed. They are primarily intended as assessment methods, and as such are unable to guide design (Cole, 2012). Current **tools** guidance are of some use in realisation of sustainability. Essentially, tools are useful to measure progress and though early design tools are available, tools appear to be of more value at a later design stage - the 'early' sequencing is therefore not fully addressed by tools, or these tools are in the wrong format. Most tools are of a technical nature and relate to outcomes that can be clearly measured, meaning many tools are used to assess not to inform decisions (Schweber, 2013).

It seems that while the body of knowledge on the theory of 'sustainable development/building/design' is growing - along with an associated increase in software, internet tools, methods and publications to act as design guidance in manipulating this theory - there still remains a consistent dearth of sustainable building both globally and specific to Ireland at present, and robust green building practices are yet to develop (Korkmaz et al., 2010). The technologies, products and guidance for sustainable building are available, but they are not successfully exploited in design (Häkkinen and Belloni, 2011). The current guidance interface is not meeting this need fully as guidance rarely addresses sequencing issues, and often issues are divided by topic or profession, and interdependencies between issues or professions are not highlighted (Lombardi, 2011). It is further suggested by the literature that as a support for sustainable design, existing sustainable design guidance such as methods and tools are useful and equally as important as process guidance but which are structured to be used at a later stage in the design process for a much more developed design, and as such process guidance is best poised to offer most assistance to inexperienced

sustainable design architects in early stage sustainable design. This calls for existing sustainable design process guidance to be questioned and perhaps enlivened to deal with the practicalities of delivering sustainable buildings.

### Design Charrette

The next phase was a design charrette, which was constructed as a “small scale experiment” involving a single test with a small number of groups (Cash et al, 2012 cited in Vallet et al., 2012); with both quantitative and qualitative aspects in its design and analysis of results. It provided an opportunity to observe design process in practice (Austin et al., 2001) and to test the applicability and validity of existing design guidance in form of process, methods and tools. It could be analogous of actual practice and process (Edwards, 2009) in order to enable characterisation of participants in relation to larger population (Vallet et al., 2012).

30 participants took part in design charrettes held over two days. Two of these participants were experienced sustainable designers recruited from an earlier interview research phase and the remaining participants were selected through an advertised open call for architects inexperienced in sustainable design. In the main participants worked on a variety of projects, were from small practices and had less than fourteen years’ experience. The participants were split into 5 groups and were given the same small group design task. Each group was given additional guidance in the form of either process, method and tool guidance, with one control and one inexperienced group given no guidance - Table 1.

Table 1. Charrette participant detail

GROUP	NO. IN GROUP	EXPERIENCE	GUIDANCE PROVIDED	FORMAT PROVIDED
Control (C)	7	Inexperienced	None	N/A
Tools (T)	6	Inexperienced	Variety of 8 software tools appropriate for early stage design regarding site ('climate consultant'), fabric (u value calculator, materials ('BEES'), comfort ('freerunner', 'designadvisor' and daylight factor calculator), energy ('design advisor') - all freely available and advertised as not requiring previous experience.	On 2 laptops with internet access, with instructions
Process (P)	7	Inexperienced	RIBA Green Overlay .This relates to UK design stages, and are mainly similar to the Irish RIAI stages. It gives sus issues to consider at each design stage.	Paper format, with instructions
Method (M)	8	Inexperienced	BREEAM 2008 for Offices - a sustainability accreditation checklist of sustainable topics and issues to consider in checklist format.	Paper and digital format, with instructions
Experts (E)	2	Experienced	None	N/A

Two surveys recorded the attitudes of participant’s pre and post design task, and were compared to annotated observations made by the author during the task. It is recognised for increased confidence in the generalizability of these findings a larger sample size would be required, however the sample size was deemed to be in line with previous studies of a similar nature (Cash et al., 2013) and appropriate for the investigative nature of this research.

The limitations to studying in this way all the design processes undergone by an architect are acknowledged; it is still a “synthetic experiment that does not carry weight equivalent to a natural experiment” (Clayton et al., 1998). However it is an approximation of process which reveals elements of real world practice which can inform and direct current sustainable design guidance and future research in these areas.

Participants were asked questions on the particular design guidance used by their group in terms of: 1) how useful it was to aid knowledge and understanding and meet sustainability targets 2) how effective it was to help to direct the design process, 3) practically how useable and understandable it was and 4) how likely participants are to use the guidance in the future. The main conclusions are summarised below.

## **Knowledge and understanding and sustainability targets**

It should be noted that pre-task the majority of the participants expressed generally that their knowledge and skill level to be 'average' or 'below average'. Participants found the process guidance most useful and the tools least useful in terms of the ability of the guidance to aid understanding and consideration of the design targets/brief. Post-task participants expressed their knowledge of sustainable design had improved, signifying that when a design process is framed with a sustainable design brief and approached from this viewpoint that sustainable design knowledge of participants can be enhanced. These findings correlate with literature findings in terms of the need for improvement in sustainable design knowledge and suggests that when the knowledge is there it can remain dormant and requires additional activation to bridge the gap between theory and its implementation in the design process.

## **Directing the design process and effect of guidance on design process**

Participants found the tools guidance least successful at aiding integration of sustainability into the design process and in aiding coordination of design activity – Figure 1. The process and method guidance are observed to be of equal success in this regard.

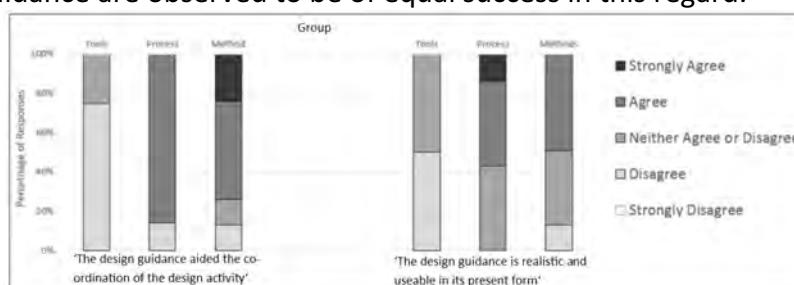


Figure 1. Responses of relevant charrette groups to given statements

Whilst on the whole the inexperienced groups P,T and M showed no major differences in terms of design activities engaged with or time spent on each design activity, there were some differences – particularly in relation to engagement with design activities (Table 2) which suggests this is in part linked to the guidance each group used, and that therefore perhaps the process guidance was more successful in eliciting a better design process response from participants than either of the Tools or Method guidance.

Table 2. Total percentage of design activities engaged with per charrette group

Group	Total % design activities engaged with (as indicated by participants)
C	62%
M	66%
T	70%
P	81%
E	75%

## **Practically useful or understandable**

The tools guidance was least understood with similar proportions understanding both the method and process guidance. Tools and method guidance is found to be the least straightforward to use by participants. Tools guidance is found to be least useable and realistic, and Process the most - Figure 1. Tools guidance is least successful in directing the design process and least relatable to existing design processes, with method and process similar.

## **Potential Future Use**

Participants were willing to use all guidance on a future project, with participants most willing to use the method guidance, then the process guidance, and then the tools. Participants expressed more strongly that the process guidance would be implemented more easily than the method, followed by the tools guidance. However, participants expressed they still

required additional guidance on how to implement sustainable design into their process. This indicates that although the design guidance used was useful in improving knowledge and skills, none of the given guidance was completely effective to enable successful implementation of sustainability and there is still the capacity and the need for a more developed or different form of sustainable design guidance for architects of this demographic in terms of *applying* sustainable design theory.

### **Where participants received no guidance**

In terms of the participants who *did not receive any additional guidance*, the Expert Group E is ambiguous in their attitudes to potential additional guidance though they are in clear agreement is in their willingness to use additional guidance. The Control Group C participants agree that potential additional guidance would be useful. Both of these findings indicates an openness and readiness that could be found amongst all participants to use and integrate sustainable design guidance into working design processes – either by inexperienced sustainable designers to enable a more effective sustainable design process or, to a lesser extent by experienced designers to advance their existing sustainable design processes.

### **Summary of design charrette findings**

In terms of the participants who *used some form of design guidance* during the task, the tools guidance was the least successful in all aspects as expressed by participants. Whilst there are a few aspects where method guidance is more successful than the process guidance these aspects are mainly related to design process management and administration issues. The process guidance is more successful than method guidance with regard to: considering design targets, effective team working, being useable, realistic and straightforward and ease of future implementation in practice; and marginally more successful in terms of understanding the guidance, having the potential to be clearer if the participants had had more time to use it and improving the process of sustainable design undertaken by architects. As such in this study it can be seen that the process guidance is most successful overall, particularly for aspects which have more weight in terms of enabling an effective sustainable design process (e.g. knowledge, understanding and practical use).

### **Proposed Process Guidance Framework**

From the research findings, the author proposes the form, content, structure, sequencing and use of guidance – Table 3. This is an initial framework to what guidance should respond to and contain and provides a basis for further research, testing and refinement. Table 3 shows an example of the framework for stage 1 of the design process 'inception'. It gives design criteria gathered from four sources for two headline issues (water and management). Please note this is a snapshot as the framework currently exists as interactive spreadsheet which covers expanded issues and design stages.

Table 3. Proposed guidance framework Stage 1; simplified

Sustainable Design Factors Headline Issues	Sustainable Design Factors Sub-Headline Issues	Design Process Stages (From RIAI workstages)			
		1. INCEPTION AND GENERAL SERVICES Sources for detail of sustainable design criteria			
		Openhouse indicators	Established and published literature and guidance for the Irish context	Interviews	RIBA Green overlay
WATER	Water efficiency		WATER: 1. Assess if the client will consider water-saving sanitary fittings - cisterns, controls and taps 2. Discuss the levels of water re-use possible - 'green', 'grey' , and 'black' water.		
	Rain Water Harvesting				
MANAGEMENT	Management				Client to consider formal adoption of soft landings approach to the project

### ***Proposed form and structure of Guidance Framework***

The author suggests the proposed sustainable design guidance should take the form of a framework which is based on a known process model structure (e.g. for Irish context - the RIAI workstages) which has a familiar structure and known context to inexperienced sustainable design architects and which could potentially be easily adjusted to other European design stages which are largely similar. Often existing guidance has been created with the transfer to industry expected to function as a self-evident automation. However, the use of the framework within or alongside a familiar structure would help to enable the assimilation of the new knowledge rather than it being an adjunct to the existing process; looking to make existing processes more sustainable instead of developing a new process (Heiskanen and Jalas, 2003 in Coley and Lemon, 2009).

The charrette findings suggest basing a guidance framework on a process model has the most potential to be successful. Using process workstages as the guidance framework basis has the potential to succeed as many practitioners refer to these workstages within their everyday design process. The purpose of the framework is therefore not to introduce new ideas but to improve and refine existing processes. Design processes evolve and change over time and a guidance framework related to the existing design process could be a trigger for this change in helping to integrate sustainable design into mainstream design process.

### ***Proposed Content and sequencing of Guidance Framework***

It is suggested the framework guidance should map the *whole* spectrum of potential sustainability goals. It is proposed this map is derived, compared and assimilated both from previous research (e.g. Openhouse indicators) and from published literature and guidance for the Irish context- Table 3. In this way many facets of sustainability could be assimilated into one area which relates very specifically to the Irish context but which would also be capable of being related easily to others. As such it would represent a more robust and holistic definition of sustainability than currently exists and enable a wider range of factors to be considered from the beginning –avoiding abortive work. The framework would ask designers and stakeholders to define and discuss project sustainability goals to help make clear any value judgements, worldviews, or ways of thinking (Wahl and Baxter, 2008) about sustainability that might otherwise go unheard and negatively influence the design process.

The charrette findings indicate that the current interface of existing processes, methods and tools guidance rarely addresses sequencing of issues, and often issues are divided by topic or profession; and therefore interdependencies between issues or professions are not highlighted; as various facets of sustainability can be affected by one design aspect; these interrelationships should be made evident (Lombardi, 2011).

Firstly sequencing of the issues should be mapped by relating the issues to *when* they should be considered in a design process (based on workstages as above) and secondly relationships between issues should be addressed by indicating which issues affect and influence other issues. In this way the framework would help a designer to translate a design process to a sustainable design process through specific actions and sequencing. As such the proposed guidance framework is intended be both comprehensive and practical to use (Schweber, 2013).

### ***Proposed use of Guidance Framework***

The framework is intended to form a guide to a better pattern of activities, not to prescribe a sequence of activities which must be performed. It is not intended as a ‘one size fits all’ – it

must be aligned to user and client needs and assembled by the designer for that particular project. By default the proposed guidance framework would indicate all the potential sustainable design factors to be considered at all stages which the design team could then refine. This is particularly useful in increasingly interdisciplinary design processes as the guidance framework can give a defined approach to enable teams to work successfully together towards shared goals which can be nurtured from the bottom up. This also reinforces the difference between this proposed guidance framework and other existing guidance interfaces in that it does not force a strict procedure, but can be adapted to suit a particular team and/or project. As the framework is directed at inexperienced sustainable designer it is expected these designers would use it only when experience is not sufficient to design a satisfying solution. Indeed, as the charrette findings have shown once architects move from inexperienced to experienced sustainable designers, i.e. towards a *sustainable* design process their need for a framework, such as this, diminishes.

The proposed framework is not intended as an assessment tool but to be a kick-start for sustainable design – an early design decision support tool to help to bridge gap between theory and practice (Magent et al., 2009). It enables architects to address a barrier in their individual control instead of waiting for bigger picture barriers to catch up (Figure 3). Even in integrated design processes, known to be best in delivering sustainability, a supportive framework could be of benefit to enable more sustainable solutions (Coley and Lemon, 2009).

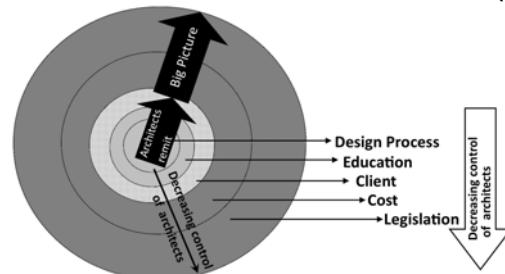


Figure 3. Levels of barriers to sustainable design implementation

## Conclusion

The aim of this paper was to explore current sustainable design guidance and propose the form it should take to enable more successful implementation of sustainable design. The intention of this study is to move the discussion forward with a focus on the *application* of sustainable design by architects in the Irish context, with a focus on early stage design.

Literature findings revealed limitations to the existing guidance available which was further established by the charrette findings. The charrette studied the importance of understanding how to *apply* sustainable design knowledge to working design practice and revealed existing guidance is not absolutely successful in achieving this - post-task participants expressed they still required additional guidance on how to implement sustainable design into their process. This indicates existing sustainable design guidance is not completely effective in its current form to enable successful implementation of sustainability within early stage design by inexperienced sustainable design architects. It was found there is still the need for sustainable design guidance for architects of this demographic which could apply to the greater population of inexperienced designers.

Notwithstanding this, charrette findings suggested the process guidance was most useful guidance overall, particularly for aspects related to knowledge, understanding and practical use and that overall, of the guidance available, design process guidance has the most potential to be successfully developed to more effectively implement sustainable design.

From this a guidance framework is proposed with the intention to assist in moving the design process of inexperienced sustainable designers towards a sustainable design process, and its proposed form, content, structure and use is based on the findings of literature and the charrette research phases. As such it is intended to respond to deficiencies highlighted within current sustainable design guidance to enable more effective implementation of sustainable design. As such it is hoped these findings will not only serve as a reference to practitioners but will aid the development of further understanding of the nature of this gap between theory and practice, and that the recommended guidance framework can give improved understanding and act as a stimulus to a more effective, useable and relevant form of sustainable design guidance for inexperienced sustainable designers than currently exists.

### **Future Work**

The proposed framework exists currently as a spreadsheet and requires further development and refinement to test its usefulness and appropriateness. Additionally the charrette findings could be further tested on larger numbers of the desired sample population.

### **References**

- Austin, S., Steele, J., Macmillan, S., Kirby, P. & Spence, R. (2001). Mapping the conceptual design activity of interdisciplinary teams. *Design studies*, 22, 211-232.
- Bordass, B. & Leaman, A. (2013). A new professionalism: remedy or fantasy? *Building Research & Information*, 41, 1-7
- Cash, P. J., Hicks, B. J. & Culley, S. J. (2013). A comparison of designer activity using core design situations in the laboratory and practice. *Design Studies*.
- Clayton, M., Kunz, J. & Fischer, M. (1998). The Charrette Test Method. Available: <http://cife.stanford.edu/sites/default/files/TR120.pdf> [Accessed 13th March 2013].
- Cole, R. J. (2012). Regenerative design and development: current theory and practice. *Building Research & Information*, 40, 1-6.
- Coley, F. J. S. & Lemon, M. (2009). Exploring the design and perceived benefit of sustainable solutions: a review. *Journal of Engineering Design*, 20, 543-554.
- Edwards, R.L. (2009). October. Design charrettes as pedagogical method in a multimedia design course. In *Proceedings of the 27th ACM international conference on Design of communication* (pp. 181-186).
- Eurostat. (2016). Energy Trends. Available: <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>.
- Korkmaz, S., Riley, D. & Hormann, M. (2010). Piloting evaluation metrics for sustainable high-performance building project delivery. *Journal of Construction Engineering and Management*, 136, 877-885.
- Hoffman, A. J. & Henn, R. (2008). Overcoming the Social and Psychological Barriers to Green Building. *Organization & Environment*, 21, 390-419.
- Häkkinen, T. & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information*, 39, 239-255.
- Irish Green Building Council. (2012). Building Environmental Assessment for Ireland. Available: <http://www.igbc.ie/c5/projects/>.
- Lombardi, D. R. (2011). Elucidating sustainability sequencing, tensions, and trade-offs in development decision making. *Environment and planning B, planning & design*, 38, 1105-1121.
- Magent, C., Korkmaz, S., Klotz, L. & Riley, D. (2009). A design process evaluation method for sustainable buildings. *Architectural engineering and design management*, 5, 62-74.
- NBS. 2012. Sustainability Survey 2012. Available: <http://www.thenbs.com/topics/Environment/articles/nbsSustainabilitySurvey2012.asp/>
- Schweber, L. (2013). The effect of BREEAM on clients and construction professionals. *Building Research & Information*, 41, 129-145.
- Vallet, F., Eynard, B., Millet, D., Mahut, S. G., Tyl, B. & Bertolucci, G. (2012). Using eco-design tools: An overview of experts' practices. *Design Studies*.
- Wahl, D. C. & Baxter, S. 2008. The Designer's Role in Facilitating Sustainable Solutions. *Design Issues*, 24, 72-83.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Norway's electric vehicle deployment success and PLEA

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**Abstract:** The huge Norwegian hydropower capacity delivering 99% of its electric energy has been the backbone of the argument for the introduction of electric vehicles since 1988. This had led to the design and implementation of the world's most generous incentives for battery electric vehicles (BEV) from 1994, an act that later led to soaring sales. In 2012, 3% of all cars sold in Norway were BEVs and Norway was the World's 5th largest volume market for BEVs. By the end of 2016 there were over 101 000 BEVs and by 2020 it is forecasted that every second car sold will be electric. However, in addition to the BEV sales, the sales of Plug in Hybrid Electric Vehicles (PHEV) have soared. In the first two months of 2017, 49% of all sold personal cars, not vans and buses, in Norway were BEVs and PHEVs. The goal is an all-electric vehicle fleet. The paper responds to three questions: 1. How did this success come about? 2. What is the link between electric vehicles and buildings? 3. What can case studies teach us?

**Keywords:** Battery electric vehicles, incentives, buildings.

### Introduction

The discourse on sustainable urbanism is often centred on densification. Dense cities generally score well in terms of greenhouse gas emissions per person. Short distances between work, home and social arenas, well-developed public transport systems and compact housing has generally been considered advantageous. Urban areas like Hong Kong, New York, Vancouver, Tokyo and London can hence show average CO<sub>2</sub> emissions per person per year below 7 tons, while more rural areas, because of the need for more transport over large distances, score less well. The USA at large is above 15 tons CO<sub>2</sub> per capita per year (Global Carbon Atlas, 2016).

Norway, scores well on Human Development Indexes every year and topped the global statistics in 2014 (HDI, 2014). But the relatively non-dense cities, and the life style results in average CO<sub>2</sub> emissions above 10 tons per person per year. This does not tell the full story of a country generally considered to be happy, social democratic, equal and rich. As an oil exporter, most of Norway's oil is burnt abroad. This is not registered on the average Norwegian's annual per person emissions. To show this full picture, in addition to the 10 tons normally shown one must add another 149 tons CO<sub>2</sub> per person per year. In this paper I will concentrate on the 10 tons and discuss how BEVs and PHEVs can play a considerable role at reducing CO<sub>2</sub> emissions.

## Densification or technology

Densification of cities takes time and the effect cannot be noticed within a decade or two in the same manner as technology shifts can. This was also the conclusion of the 2005 Low Emission Report (Randers, 2006). It showed clearly that during a 45-year time span, densification will not have much effect, while technology shift in the transport sector will. As shown in Figure 1 densification leading to reduced need for transportation (Transportredusjon) only showed the potential for marginal reductions up to 2050.

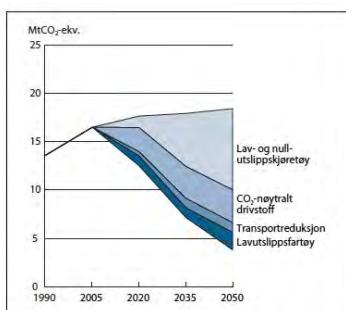


Figure 1. The Low Emission Report concluded that it would be much easier to reduce emissions through technological improvements than through densification (Transportredusjon).

The construction of new buildings also takes time. Although there are strong upcoming regulations regarding energy efficiency and the use of renewable energy leading to a new energy paradigm as shown in the new EU Directive (ED, 2010) stating that all new buildings from 2020 have to adhere to the Net Zero Energy Building level (NZEB), it will take decades to reduce the energy need in existing buildings. This is because buildings, as opposed to vehicles, have a very long life and are constantly adjusted. They last from 40 to 150 years at least, while a vehicle fleet is normally completely shifted, scrapped, recycled in less than 20 years. The current vehicle fleet in Norway is now 10,5 years old. This is relatively old compared to other European countries and a result of extremely high taxes on cars making them very expensive. The EU vehicle life average is much younger, only 7,4 years. Norwegian vehicles are on average scrapped or recycled after 19 years (VG, 2017 p12).

Replacing the existing fleet's oldest and very polluting cars is hence a strategy that can be implemented relatively fast, compared to replacing polluting buildings with new ones. This paper will hence concentrate on studying the shift with the biggest impact up to 2050, namely technological improvements of the vehicle fleet exemplified through the case of Norway. The paper will look at three main issues:

- How did the Norwegian BEV success come about?
- What is the link between electric vehicles and buildings?
- What can case studies teach us?

### How did the Norwegian BEV success come about?

In 1987, the UN World Commission on Environment and Development, headed by the Norwegian Prime Minister Gro Harlem Brundtland released its report "Our Common Future". Its conclusions were clear and recommended action to be taken to stop damaging the environment. But instead of becoming a fine example, Norway started to intensify its oil exploration and exports grew.

In 1988, and as a reaction to the double standards, a small group of Norwegians consisting of an energy- and transport expert, an environmentalist and a famous singer joined forces and decided to design a strategy to force the Norwegian Government to introduce strong incentives for electric vehicles to test their ability and willingness to put the UN report into practice and show the direction forward.

As a step one, they travelled to Switzerland to watch the annual solar electric vehicle race over the Alps, the “Tour de Sol”, after which they visited the race-related solar electric vehicle exhibition in Bern. Until then it had been difficult to get media attention for electric vehicles in Norway and the expert that initiated the “expedition” had hence decided to join forces with the two others. This worked well. Suddenly all the major Norwegian media, nationwide TV and national newspapers wanted to come along, since a celebrity singer was inviting and the event was thoroughly media covered. This led to growing electric vehicle curiosity in Norway. When the three-person group the year after in 1989 bought and imported the first electric vehicle to Norway the same media covered the event and the planned step two was accomplished. Step three of the plan was to drive the vehicle in the toll roads around Oslo, the capital, without paying toll road passings.

As the famous face of the pop star and by now, the famous face of the environmentalist, appeared on TV because of refusal to pay toll road passing, people felt it was a developing story like a series with unknown outcome. When the unpaid bills piled up, step four was unavoidable. The state secured their debt by taking the electric car into custody and it was sold at a public auction. The media was there and embarrassed the state officials. The auction resulted in a bid from a person sympathetic to the environmental cause. He bought the car and gave it back to the group and it continued to drive through the toll road passing without paying. Months later, the same procedure occurred, the state took the vehicle and sold it. Someone bought it and gave it back. After several rounds of this over a couple of years and always with the press up front in the audience, the group’s demands were granted.

When one of Europe’s first modern energy autonomous housing projects was completed at the Building for the Future exhibition in Stavanger, Norway in 1988, the imported vehicle was filmed while it connected to the solar PV system of the house, to charge its battery. The world’s best BEV incentives were thereafter one by one implemented. The BEV incentives were introduced one by one always following a fight and today they still remain more or less as composed back in the 1990s. They have led to a situation where BEVs are fully cost competitive with other cars. The first electric bus in regular traffic in Scandinavia was put into operation in 1994 (Figure 2).

The list of incentives and the year they were implemented are shown below:

- 1990: Temporary abolishment of import tax.
- 1996: Reduced annual electric vehicle registration tax.
- 1996: Permanent abolishment of import tax.
- 1997: Exemption from road toll.
- 2000: Reduced company car tax.
- 2001: Zero VAT, a reduction from the former 25% VAT.
- 2005: Access to bus lane nationwide.
- 2009: Free access to road ferries.



Figure 2. Trying an electric vehicle in Bern (left). The bought one, a Fiat Larag electric being charged at one of Europe's first modern energy autonomous housing projects in 1989. In 1994 Scandinavia's first electric bus in regular traffic was introduced in Stavanger (right). It had interchangeable batteries.

### The current situation

Norway has the 19<sup>th</sup> highest national car ownership in the world with 498 cars per 1 000 population (The Economist, 2017). With its five million inhabitants it is viewed as one of the most important countries for electric vehicles and a laboratory for research and testing out incentives, new models and driving modes. Norway is long; from its Southern tip to the Northern one is similar to the distance from Oslo to Rome. There are hills and flat land, rugged roads and motorways and the climate varies considerable from area to area. There are freezing inland mountain areas where frostbites occur as temperatures occasionally drop to extremely cold minus 35 C, while simultaneously the coastal areas are mild and above zero.

There are now more than 101 126 BEVs in Norway. More than 25 000 BEVs were sold each year during 2015 and 2016. In 2016, 15,7% of all sold vehicles were battery electric and the sale of hybrid vehicles rose to or 13,4%. In sum 29,1% or 154 603 vehicles of all sold vehicles in 2016 were BEVs and PHEVs (OVE, 2016). The comparable sum figures for Denmark is only 4% and Sweden 8%.

The data for the start of 2017 show that 48% of all new vehicles sold in Norway during January and February were BEVs and PHEVs. A silent and dramatic shift has taken place and a worry among owners of diesel and petrol fuelled cars that they might not be able to find a second hand market soon, if this development continues, is spreading.

While the existing total fleet of vehicles in Norway today has an average emission of 188 grams CO<sub>2</sub> per vehicle kilometre, the average of all sold vehicles in January 2017 were only 84 grams (VG, 2017 p66). There are now PHEVs on the market that have emissions as low as 21 grams CO<sub>2</sub> per vehicle kilometre (Toyota, 2017).

### What is the link between electric vehicles and buildings?

The tremendously fast and positive development in battery technology for the electric vehicle sector has resulted in side effects that could have a considerable impact on the building sector. Charging of BEVs and PHEVs take place both at home, at work and in the urban landscape. When vehicles connect to buildings the possibility of sharing electric storage space occurs. With all the battery packages now available for vehicle charging a new energy storage option is made available in buildings. This offers a completely new possibility for utilizing the battery in the vehicle and/or a stationary battery bank as energy storage.

There is, however, a condition for making this realistic: The energy need in the building has to be lowered. This can be achieved through the classical passive and low energy measures like designing buildings so they use as much daylight as possible to save the use of electric light, use natural ventilation whenever and wherever possible, use passive solar heating without overheating. By lowering the need for bought energy, the

application of new, renewable energy becomes more realistic because it becomes less costly when the energy system size is reduced. Passive methods, energy efficiency and the use of new renewable energy is hence the very foundation necessary to bring in vehicle sector battery storage sharing as an option, simply because the need for energy in buildings becomes so small that the battery size becomes realistic.

An advantage of limited size battery storage is that it combines cost effectiveness with the possibility of evening out morning (breakfast time) and afternoon (dinner time) energy peaks. This helps the electric utility to plan ahead with more rational systems, eliminating costly capacity peaks. Such building/vehicle battery sharing solutions can be extended to become neighbourhood solutions connecting with local decentralised new renewable energy systems like solar and wind on building facades, roof and in the surrounding landscape as well as combining the energy from them with geothermal heat pumps.

Whether the approach of forcing authorities to go in a certain direction as regards incentives as described for the BEV sector can be applied to the architecture and planning sector is hard to answer. Certainly, sometimes, a more outspoken and action orientated profession might manage to question cemented truths and authorities, than an obedient profession. But at other times the outcome is the opposite, so there does not seem to be a golden rule or learning experience from the BEV case that can be transferred to another sector. What certainly can work though is to strengthen the architectural profession so that it makes use of its ability to convince clients to move in a more sustainable direction. There are also several ethical issues related to this and it can be argued that it is a moral obligation for the profession to work for more sustainable solutions, given the dramatic and negative consequences of climate change leading to millions of humans suffering and a general degrading of the human condition on Earth.

### **What can case studies teach us?**

Freiburg is often described as the environmental capital of Germany. Architects, planners and technologists go there to study the technical gadgets of its solar buildings and its transport systems. But few ask how Freiburg managed to achieve its sustainability goals. Was it technology alone? Not at all! It was a holistic approach that started in the 1970s and 80s by environmental activists that were fighting against the construction of a new nuclear power plant in the region. There was also the Fraunhofer Institute and the solar architecture of German architect Rolf Disch and the environmentally conscious inhabitants in the region. They made it possible to develop Freiburg to what it has become. They were receptive to new environmental ideas and this pushed politicians in a green direction that led to the introduction of the sustainability policies that were later implemented. In a study asking which factors are important in Freiburg for sustainable urban development, many factors were scoring well, but the highest score with 70% of respondents ticking off this box, was *Conscious population* (Muller-Eie et al, 2016).

In another case, this one in Norway at Madla Revheim in Stavanger, a new city-part for 10 000 people is being developed using the method of public participation (Figure 3). The planning process has been concentrating on involving both people in the area, potential contractors, housing corporations and industry actors in order to try to create an environmental-positivism years before the actual building will start. It is all about public participation. The energy strategy is also developed and based on trying to communicate a goal to the public. At the core of the strategy are energy efficiency, new renewable energy and an all electric vehicle and bus fleet. The study so far shows that such an all-electric

approach is possible technically and it is viable economically, provided energy efficiency is at its base, but the people must also be brought in and informed about the visions and the consequences of implementing it.

While this study was carried out, we became aware of hundreds of other cases with similar content. The architectural, engineering, mobility and scientific literature frequently carries reports and essays on the issue of the link between an all electric vehicle fleet and buildings. In a recent book that came about as a result of IEA Task 40 "Towards Net Zero Energy Solar Buildings", feedback from thirty built cases of NZEBs were described (Garde et al, 2017). The solution sets described all had the possibility to link the mobility sector with the buildings sector through sharing of electric energy, in much the same way as the Madla Revheim project proposed. The tremendous development in battery technology happening as a result of advances in the electric mobility sector, where not only road vehicles but also electric boats and planes are being developed, planners and architects must make sure they stay updated and see the potential. Buildings have a long life and cannot easily change. It is hence crucial that planners have a time-perspective catering for several kinds of possible changes.

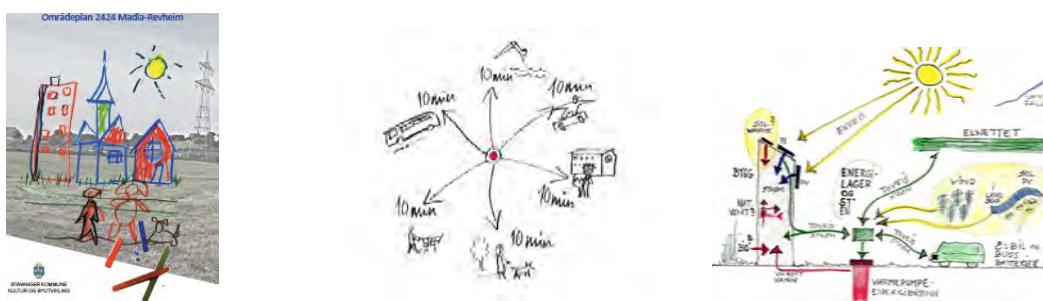


Figure 3. Madla Revheim, Norway. A new part of the city Stavanger for 10 000 people plus schools, commercial and social activity is designed around a strategy of passive and low energy. Measures and new renewable energy connecting buildings and vehicles.

## Conclusions

The Norwegian electric vehicle incentives are a success story. They came about through radical actions by an unusual mix of people that managed to achieve sympathy for the cause among the average man and this led to the Government bending over and granting all demands. Later this success story has been further strengthened by a national plan to deploy fast charging station throughout the country so that one can drive practically anywhere without losing time. The national network of fast charging stations is now under construction. In addition stringent regulations are put in place through the National Transport Plan 2018-2029 (NTP) to promote and provide incentives for electric goods vehicles, boats and ferries. The experience from the vehicle sector can and is applied to the building sector as vehicles and buildings are finally beginning to "talk" together and to share each other's stored energy.

To bridge the gap between the mobility sector and the building sector requires an understanding of the other sector. This expansion of the understanding of another sector than one's own will become important in the process of developing a more holistic environmental thinking among planners and architects as well as mobility actors. Such an expansion must happen early in life, during the education in the different fields, to avoid the growth of cemented "truths" that limit the ability to see new exciting possibilities.

## References

- Aftenposten, (2017). *Grønt skifte på norske veier*. Aftenposten Innsikt No 2, February 2017.  
Data based on TØI and Cisero.
- ED, (2010). EU Directive ED 2010/31EU on Nearly Zero Energy Buildings.
- Elbil, (2017). elbil.no/English/Norwegian-ev-market/
- Garde, F. et al, (2017). *Solution sets for Net Zero Energy Buildings*. Wiley VCH. ISBN 978-3-433-03072-1.
- Global Carbon Atlas, (2016). <http://www.globalcarbonatlas.org/en/content/welcome-carbon-atlas>  
Accessed 27.02.2017.
- HDI, (2014). <http://www.globalis.no/Statistikk/HDI-menneskelig-utvikling>
- Muller-Eie, D., (2016). *Bærekraftig byliv I Freiburg – hva kan vi lære?* Plan 5/2016. pp50-55.  
ISSN 1805-083X.
- OVE, (2016). <http://www.ofvas.no/bilsalget-i-2016/category706.html> Accessed 27.02.2017.
- Randers, J. (2006). *Et klimavennlig Norge. NOU 2006:18*, p65. Lavutslippsutvalget.
- The Economist, (2017). *Pocket World Figures. 2017 Edition*, p76. The Economist. ISBN 978 1 78125 607 7.
- Toyota, (2017). Toyota Pris Plug in Hybrid launched March 2017.
- VG, (2017 p12). *Fakta*. VG Helg 14 January 2017, p12.
- VG, (2017 p66). *Fakta*. VG Helg 18 January 2017, p66.

## Key

Vehicles = personal vehicles, not vans and buses.

BEV = Battery Electric Vehicles.

PHEV = Plug in Hybrid Electric Vehicles.



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*Design to Thrive*

## Application of LCA results in the early design phase of environmental-friendly buildings

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**Abstract:** Buildings are responsible for a significant impact on the environment during their life cycle. For the design of an “environmental-friendly” building, the environmental impacts of aspects including the manufacturing of construction materials, operation and maintenance, demolition and disposal, and related transportation should be analysed from “cradle to grave”. A variety of models have been developed to calculate the life cycle environmental impacts of buildings. However, attempts to find common criteria or principles for design decision making from the results of previous studies is problematic because different studies determine life cycle assessment (LCA) results using a varying series of assumptions and a variety of different parameters. Because of their complexity, LCA quantification methods are not generally employed by building designers at the early design stages when they may be of most benefit. The aim of this study is to elaborate the difficulty of generalising results from previous LCA studies and therefore the difficulty of developing elementary heuristic principles to assist designers, by highlighting the complexity of LCA tool and providing examples of life cycle energy assessment in residential buildings. The results highlight the main problems designers would encounter trying to use the LCA method at the early design stages, and the need to develop heuristic guidelines for designers to allow them to understand the most effective design variables on the building life cycle performance.

**Keywords:** LCA; environmental impact; early stage design; rules of thumb; material selection.

### Introduction

Minimizing impacts on the environment is an important goal for the building sector. Energy is generally one of the most important resources consumed by buildings over their lifetime (Thormark., 2001). If no action is taken to improve energy efficiency, energy demand in the building sector is expected to rise by 50% by 2050 largely because of the rapid growth in the number of households, increasing building floor areas, higher ownership rates for existing electricity-consuming devices and increasing demand for new energy consuming products (IEA, 2013).

Buildings not only impact the environment through energy consumption and greenhouse gas emissions, they also negatively impact aspects such as water use, waste generation and resource depletion (Stephan et al., 2013). Rapid urbanization in developed and developing countries is expected to increase demand for new housing and more comfortable living environments and therefore further exacerbate these impacts (Ortiz et al., 2009).

Because buildings consume materials and energy across their whole life, they need to be analysed in terms of their life cycle. Construction and occupation are the two main

phases of a building's life cycle. Life cycle assessment quantifies potential environmental effects of a building during its life cycle, starting from extraction of raw materials to its demolition and waste management.

Many attempts have been made to quantify the total environmental impacts associated with buildings through their life cycle. However, quantification methods are not generally employed by building designers at the early design stages when they may be of most benefit. The aim of this study is to elaborate the difficulty of generalising results from previous LCA studies and therefore the difficulty of developing elementary heuristic principles to assist designers, by highlighting the complexity of LCA tool and providing examples from 18 case studies of life cycle energy assessment in residential buildings. The results highlight the main problems designers would encounter trying to use the LCA method at the early design stages, and the need to develop heuristic guidelines for designers to allow them to understand the most effective design variables on the building life cycle performance.

### **LCA and the features**

LCA is a tool for systematically analysing environmental impacts of the products or processes over their life cycle. LCA is often considered a "cradle to grave" approach to the evaluation of environmental performance and includes all important phases of LCA of a product, particularly the extraction of raw materials from the natural resources, materials' production, the final outputs, their use, waste removal/recycling, and all related transportation (Cabeza et al., 2014, Klöpffer, 2014).

Different LCA approaches have different emphases when determining environmental impacts. Life cycle energy analysis (LCEA), for example, focuses on energy and accounts for all energy inputs to a product. This not only includes direct energy inputs during manufacture, but also all energy inputs for producing components, materials and services needed for the manufacturing processes. Life cycle cost assessment (LCCA) of buildings, on the other hand, measures impacts in terms of cost. LCCA thus analyses the total cost of facility ownership, including all costs of acquiring, owning and disposing of a building or building system (Cabeza et al., 2014). Another approach, life cycle environmental impact (LCEI) assessment measures environmental impacts that include pollutant emissions.

The International Organisation for Standardisation (ISO14040, 1997) highlight four steps for all these LCA approaches: goal and scope definition; life cycle inventory (LCI); impact assessment; and interpretation of results. Goal and scope definition explain the purposes, audiences, and system boundaries; the LCI engages with data collection and calculation to calibrate materials and energy inputs and outputs of a system; the potential environmental impacts, based on the LCI, are appraised by impact assessment (Ramesh et al., 2010).

### ***Life cycle energy analysis (LCEA) of Buildings***

For this paper, LCEA has been chosen as the basis for discussion, both because it uses the simple quantifiable measure of energy appropriate to this brief paper, and because it is commonly used for building LCA. The significant consideration of LCEA is the formulation of strategies for reducing a buildings' primary energy use and thereby controlling emissions (Ramesh et al., 2010). Life cycle inventory (LCI) as one of the four phases of LCA, including LCEA, requires a methodical approach for collecting the necessary data. Three main methods of LCI can be applied to quantifying the various inputs and outputs of products or

processes: process analysis, input-output analysis and hybrid analysis. Process analysis, based on data related to specific processes or products in a given location, quantifies the inputs and outputs and the resulted environmental impacts through the life cycle of these processes or products. Today, many countries, including Australia, Europe (e.g. Swiss EcoInvent® database), Japan, the USA and Canada (e.g. Athena Institute® database), provide databases of detailed process data for a large array of products. However, using this data is problematic because of lack of simplicity and accuracy, and the incompleteness of the system (Stephan, 2013). Input-output analysis (I-O analysis) uses national average data for each sector of the economy. It is a complete description of the system at a whole sector scale. I-O analysis can potentially solve the main weakness of the process analysis method, however it fails to provide accurate figures for specific processes or products. Hybrid Analysis is a combination of process and input-output analysis intended to minimise the limitations of both (Stephan, 2013, Crawford, 2008).

### ***Main life cycle energy demands of buildings***

When calculating LCEA, most recent studies determine the life cycle energy demand of buildings using the following phases (Stephan, 2013, Dixit et al., 2010, Ramesh et al., 2010):

*Embodied energy (EE)* is the amount of energy required during all processes of production, on-site construction, and final demolition and disposal. The overall energy sequestered in buildings and building materials has two primary components: direct and indirect energy. Direct energy is the energy consumed in on-site and off-site operations such as construction, prefabrication, assembly, transportation and administration. Indirect energy is responsible for energy consumed in manufacturing the building materials, and in renovation, refurbishment and demolition processes of the building. These comprise initial embodied energy, recurrent embodied energy and demolition energy.

*Initial embodied energy (IEE)* is all the consumed energy during the production of materials and components and including raw material procurement, building material manufacturing and finished product delivery (transportation) to the construction site. This energy can vary to a large extent between various building assemblies designed for the same function.

*Recurrent embodied energy (REE)* is the energy used in all maintenance and refurbishment processes during the useful life of a building. During a building's use phase, the components with a shorter lifespan than the building's useful life will need to be replaced (because of programmed differential lifespans, poor design or poor maintenance regimes).

*Demolition energy (DE)* is energy used in the processes of a building's demolition and disposal of building materials. Several studies have ignored this in the LCEA as studies (Crowther, 1999) have shown that it may only be responsible for 1% of the total life cycle energy.

*Operational energy (OE)* is expended in maintaining the indoor environment and is usually consumed by heating/cooling the building, mechanical ventilation, domestic hot water, lighting, appliances and cooking. Annual operational energy is primarily influenced by user behaviour, location, and the type of power of the systems. Life cycle energy is the sum of each of the above energy consumption components through the building life time (Ramesh et al., 2010).

## **Case studies review**

Review of the case studies aims to highlight the difficulty of generalising the LCA results from previous studies. For consistency all case studies reviewed have used LCEA and are residential buildings as they have the most significant environmental impacts (U.N.H.S Programme, 2009). The case studies selected use LCEA to consider the effect on energy demand of material selection for different building's elements. Table 1 presents 18 case study buildings. The influential factors affecting the amount of operational and embodied energy in these cases are classified as follows: Building location (country/ city); building type and net indoor floor space; structural typology; building lifetime; and energy calculation method. The different materials employed for roof, façade and the ground are all specified for each case but for brevity are not listed on the table.

## **Discussion**

The LCA of buildings is a complicated and time/cost-consuming procedure. The following section firstly discusses the LCA process generally in terms of the limitations for transforming it into a tool that could be employed at the early phase of designing, and secondly discusses the reviews of the case studies and the insights they contribute to understanding the limitations for transforming LCA into a tool that could be employed at the early phase of designing.

### ***Limitations arising from analysis of the LCA process generally:***

- The first step of LCA — goal and scope definition — has the potential to make previous studies incomparable and therefore inhibit the development of the sort of generalised advice that would be useful at the early design phase. Beginning the analysis using different functional units, reference flows and system boundaries complicate the possibility of having comparable data.
- Because the databases that are used as the bases for calculating LCA may not be comprehensive and may be different for different countries, the findings from case studies are not always readily compatible.
- The environmental inputs and outputs of each design combination are classified using a range of quite different impact assessment that might include energy usage, cost, CO<sub>2</sub> emissions, pollutants, and material toxicity. This makes the development of comparable impact unfeasable .
- Interpretation, which is the last step in the LCA methodology, presents results, limitations and recommendations. But because the first three steps significantly affect this last step and the first three steps as discussed may already have incomparable outcomes, any attempt to generalise in the last step is made problematic.
- Reliable and consistent results depend on a comprehensive LCA which include all life cycle phases. However, this requires the assessment of many different materials, components and processes for which information is not always available. Exacerbating this is evidence from a previous small study by the author (Bashirzadeh Tabrizi et al., 2016a) that indicates the level of complexity and certainty/uncertainty is different in each LCA phase.

Table 1. Case studies and the influential parameters.

Case Study Reference	Location (Country/City)	Type	Structural Typology	Life time (Yrs.)	Calculation Method	Results (GJ/m2)					
						EE		OPE			DE
						I	R	H	C	HW	E
1/(Aye et al., 2012)	Australia (Melbourne)	multi-storey 3943 m <sup>2</sup>	Prefab modular Steel	50	I-O-based hybrid analysis	+ - 14.4		+ + - -		21.58	N/A
2/(Aye et al., 2012)	Australia (Melbourne)	multi-storey 3943m <sup>2</sup>	Timber structure	50	I-O-based hybrid analysis	+ - 10.49		+ + - -		21.16	N/A
3/(Aye et al., 2012)	Australia (Melbourne)	multi-storey 3943m <sup>2</sup>	Conventional Concrete	50	I-O-based hybrid analysis	+ - 9.64		+ + - -		20.26	N/A
4/(Bribián et al., 2009)	Spain (Aragon)	Single house 4floors, 107.6m <sup>2</sup>	N/A	50	I-O-based analysis	+ - 5.69		+ + + -		12.66	N/A
5/(Dodoo et al., 2014)	Sweden (Växjö)	Multi-storey 42-78m <sup>2</sup> (60 m <sup>2</sup> )	Light Timber frame/CLT system	50	Process-based Analysis	+ - 4.02		+ + + +		32.66	0.04
6/(Mithraratne and Vale, 2004)	New Zealand (Auckland)	1 floor house 94 m <sup>2</sup>	Prefab timber framed/Light construction	100	Economic I-O-based	+ - 4.42		+ - - -		12.59	N/A
7/(Mithraratne and Vale, 2004)	New Zealand (Auckland)	1 floor house 94 m <sup>2</sup>	Prefab timber framed/Concrete construction	100	Economic I-O-based	+ - 4.76		+ - - -		11.53	N/A
8/(Mithraratne and Vale, 2004)	New Zealand (Auckland)	1 floor house 94 m <sup>2</sup>	Prefab timber framed/Super insulated	100	Economic I-O-based	+ - 5.04		+ - - -		6.74	N/A
9/(Paulsen and Spusto, 2013)	Brazil (Brasília)	Single family House 48 m <sup>2</sup>	Masonry	50	I-O-based	+ - 7.2		- - - +		17.5	0.27
10/(Ramesh et al., 2012)	India (Hyderabad)	Single family, house 85.5 m <sup>2</sup>	N/A	75	I-O-based	+ - 7.83		+ + + +		46.98	N/A
11/(Rauf and Crawford, 2013)	Australia (Melbourne)	Single storey house 291.3m <sup>2</sup>	Traditional timber construction clad with plasterboard internally	50	I-O-based hybrid analysis	+ + 21.32		+ + + +		14.75	0.36
12/(Rauf and Crawford, 2013)	Australia (Melbourne)	Single storey house 291.3 m <sup>2</sup>	Traditional timber construction clad with timber weatherboard internally	50	I-O-based hybrid analysis	+ + 25.02		+ + + +		14.75	0.4
13/(Rossi et al., 2012)	Belgium (Brussels)	Single storey house 192	Steel frame	50	Statistical analysis of material	+ - 4.39		+ + + +		49.39	N/A

		$m^2$			databases			
14/(Rossi et al., 2012)	Sweden (Luleå)	single storey house $192 m^2$	Steel frame	50	Statistical analysis of material databases	+ - 4.71	+ + + + 59	N/A
15/(Rossi et al., 2012)	Portugal (Coimbra)	Single storey house $192 m^2$	Steel frame	50	Statistical analysis of material databases	+ - 4.39	+ + + + 31.45	N/A
16/(Stephan et al., 2012)	Belgium (Brussels)	Passive House $330 m^2$	Steel-framed	50	I-O-based hybrid analysis	+ + 25.83	+ + + + 17.89	N/A
17/(Stephan et al., 2012)	Australia (Melbourne)	7-Star house $297 m^2$	Timber-framed	50	I-O-based hybrid analysis	+ + 23.40	+ + + + 28.91	N/A
18/(Stephan et al., 2012)	Australia (Melbourne)	Single family House $240 m^2$	Timber-framed	50	I-O-based hybrid analysis	+ + 26.39	+ + + 30.39	N/A

I-O=Input-Output, EE=Embodied Energy, OPE=Operatioanl Energy, DE=Dimolition Energy, I=Initial, R=Recurrent, H=Heating, C=Cooling, HW=Hot Water, E=Electricity

### ***Limitations arising from analysis of the case studies***

- Defining the relative importance of operational and embodied energy in a building's life cycle is still not clear. Some previous studies show that embodied impacts (raw material extraction, processing, manufacture, transportation and construction) can be as significant as operational energy. However, there is limited consistent and comprehensive information available for building designers to make informed decision in this area. Comparing case studies 11,12,16,17 and 18 which analysed IEE and REE to other cases shows the ratio of EE and OE in the building's LCEA is not consistent.
- Improvements to operational efficiency and thermal performance and efficiency of appliances and systems within buildings are typically the centre of attention of environmental decision-making during the building design process, so the results are not comprehensive. For example, in case 16, if only the amount of operational energy was analysed the building's total energy demand would lead to an incorrect result for the passive house. In this case, EE significantly affects the building's total life cycle energy demand.
- Additional criteria throughout the comprehensive LCA could significantly affect the results. For instance, in cases 6, 7 and 8, the 100 years of building lifetime means most of the materials would need to be substituted and this would significantly change the EE results. Moreover, the compatibility of the building and materials lifetimes and maintenance requirements and methods should be considered when the recurrent embodied energy is assessed. However, different estimations and assumptions for the components' embodied energy in various studies alter the results between studies (Building's lifetime/materials' service life).
- The quality of results from operational and embodied energy assessments are not reliable because the influential factors are unclear and vary greatly. For instance, considering energy demands for heating, cooling, hot water and appliances affects the

OE proportion of the building LCEA. So the interpretation of quantitative results of case studies 6, 7 and 9 would be dramatically different to others. (It is important to notice what types of energy consumptions were included for operational energy assessment.)

- It is not possible to identify the most effective parameters on the buildings' life cycle energy demands by reviewing these cases as there is no classification or prioritization of effective variables.

## Conclusions

While significant research has been conducted on the environmental impact of buildings, the knowledge about the type and quantity of information from quantitative LCA models is still limited. This information is not available when the designers make strategic design decisions in the early stages which will influence the whole lifetime environmental cost of the building. This study elaborates the difficulty of generalising results from previous LCA studies and therefore the difficulty of developing elementary heuristic principles to assist designers at the early design stages. Reviewing the LCA tool, its features and the results from selected analysed case studies in which the LCA were applied as the assessment tool, it can be concluded that:

- Life cycle energy assessment process is complex, and the existing analyses found in research are all case studies of one or a few buildings. The applicability of their results to other buildings in other areas is not clear. Comparing these studies is also complicated due to the difficulties and variability in their analysed data. For instance, the calculation method plays a crucial role in these results and applying different analysis techniques or/and different life cycle phases is primarily responsible for the imperfections of previous studies of the LCEA of the buildings.
- Moreover, building envelopes are known by researchers as a responsible for more than half of the embodied energy distribution and the total heat gain in residential buildings. However, it is still not clear which variables have more impacts. Therefore the individual effect of each variable on energy performance and dependencies between them must be defined clearly for designers in the early design stages.
- There is still a lack of accurate data on the embodied energy and the environmental parameters of the materials and manufacturing processes applied in different countries. Thus, international and well known databases used by many current LCA studies may lead to unreliable results for any national assessment.
- Most of the published studies yield the ranges of embodied energy of buildings or components by applying data from primary material sources, transportation, manufacturing processes and their own estimations and assumptions which differ from case to case.

Overall, interpretations and comparisons of previous study's results are not readily usable in the early decision-making stage by building designers. This small study thus indicates that there may be potential value in developing simple guidelines to help designers to consider the most effective parameters on the life cycle environmentally friendly building design in terms of the individual character of each project.

## References

- Aye, L., Ngo, T., Crawford, R. H., Gammampila, R. & Mendis, P. 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, 47, 159-168.

Bashirzadeh Tabrizi, T., Hill, G. & Aitchison, M. Using LCA to Assist the Selection of Wall Systems in the Early Stage of Building Design 50th International Conference of the Architectural Science Association 2016a Adelaide, Australia. The Architectural Science Association and The University of Adelaide.

Bribián, Z. I., Aranda Usón, A. & Scarpellini, S. 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44, 2510-2520.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G. & Castell, A. 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394-416.

Crawford, R. H. 2008. Validation of a hybrid life-cycle inventory analysis method. *Journal of Environmental Management*, 88, 496-506.

Crowther, P. 1999. Design for disassembly to recover embodied energy. *Proceedings of Passive and Low-Energy Architecture, Melbourne*.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S. & Culp, C. H. 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, 42, 1238-1247.

Dodoo, A., Gustavsson, L. & Sathre, R. 2014. Life cycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings. *Energy and Buildings*, 81, 84-97.

IEA 2013. Transition to Sustainable Buildings ,Strategies and Opportunities to 2050.

Iso14040 1997. Environmental Management—Life Cycle Assessment—Principles and Framework,.

Klöpffer, W. 2014. *Background and future prospects in life cycle assessment [electronic resource]*, Dordrecht :, Springer.

Mithraratne, N. & Vale, B. 2004. Life cycle analysis model for New Zealand houses. *Building and Environment*, 39, 483-492.

Ortiz, O., Castells, F. & Sonnemann, G. 2009. Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23, 28-39.

Paulsen, J. S. & Spoto, R. M. 2013. A life cycle energy analysis of social housing in Brazil: Case study for the program "MY HOUSE MY LIFE". *Energy and Buildings*, 57, 95-102.

Ramesh, T., Prakash, R. & Shukla, K. K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, 42, 1592-1600.

Ramesh, T., Prakash, R. & Shukla, K. K. 2012. Life cycle approach in evaluating energy performance of residential buildings in Indian context. *Energy and Buildings*, 54, 259-265.

Rauf, A. & Crawford, R. H. 2013. The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. *Architectural Science Review*, 56, 252-261.

Rossi, B., Marique, A.-F. & Reiter, S. 2012. Life-cycle assessment of residential buildings in three different European locations, case study. *Building and Environment*, 51, 402-407.

Stephan, A. 2013. *TOWARDS A COMPREHENSIVE ENERGY ASSESSMENT OF RESIDENTIAL BUILDINGS*.

Stephan, A., Crawford, R. H. & De Myttenaere, K. 2012. Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings*, 55, 592-600.

Stephan, A., Crawford, R. H. & De Myttenaere, K. 2013. A comprehensive assessment of the life cycle energy demand of passive houses. *Applied Energy*, 112, 23-34.

Thormark., C. 2001. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment* 37 (2002) 429 – 435.

U.N.H.S Programme 2009. Planning sustainable cities : global report on human settlements *In: PROGRAMME*, U. N. H. S. (ed.). London; : Sterling, VA: Earthscan.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## REALISING INTENTIONS: An evaluation of green building rating tools for Australian buildings

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**Abstract:** With growing concerns for enhancing sustainability, much attention has been paid to benchmarking performance in buildings. This paper evaluates the effectiveness of three rating systems that have been widely adopted for over a decade in Australia namely: (i) mandatory compliance under Section J (Energy Efficiency provisions) in the National Construction Code of Australia (NCC), (ii) a voluntary design rating tool - Green Star, and (iii) a voluntary operational rating tool-National Australian Building Environmental Rating Scheme (NABERS). The paper builds on the authors' experience in building performance simulation, rating tool design, practice consultancy and post occupancy evaluations of buildings. It presents a detailed analysis of the rating tools with respect to the alignment between what is being assessed, how it is assessed and administered and the impact on design process and performance outcomes in buildings. The paper assesses the successes and shortcomings of the rating tools to demonstrate the potential for design and post occupancy rating tools to influence market behaviour and building performance and argues for increasingly stringent approaches to get to net zero emissions.

**Keywords:** rating tools, design targets, actual performance, resilience

### Introduction

To meet the Paris 2C target, human greenhouse emissions need to halve each decade for the next three decades (Rockström et al 2017). The US EPA (2008) estimates that buildings are responsible for 38% of all human GHG emissions (20% residential, 18% commercial). The Intergovernmental Panel on Climate Change (IPCC, 2007) states that this sector presents the most cost effective opportunities for GHG reductions, ie., that buildings represent the low hanging fruit. This paper evaluates the effectiveness of three rating systems that have been widely adopted for over a decade in Australia namely: (i) mandatory compliance under Section J (Energy Efficiency provisions) in the National Construction Code of Australia (NCC), (ii) a voluntary design rating tool - Green Star, and (iii) a voluntary operational rating tool-National Australian Building Environmental Rating Scheme (NABERS).

Our emphasis is mainly with respect to questions of mitigation of greenhouse gas emissions and the intersection of these aspects with the ambition of resilience and thriving cities. Consequently this paper goes beyond direct questions of energy consumption in buildings to consider indoor environmental quality and location and transport effects as well as outcomes for occupants. On the other hand this paper does not extend analysis to materials, water, waste and landscape ecology dimensions of thriving cities. The paper builds on the authors' experience in building performance simulation, design, review and

application of rating tools, practice consultancy and post occupancy evaluations of buildings. It presents a detailed analysis of the selected rating tools with respect to the alignment between what is being assessed, how it is assessed and administered and the impact on design process and performance outcomes in buildings. Following an overview of the key rating tools, we present a thematic review of their successes and shortcomings.

## **Overview of Rating Tools**

### ***Section-J (Energy Efficiency provisions) of the National Construction Code (NCC) of Australia***

These provisions cover minimum mandatory energy efficiency provisions for all buildings. The stringency limits and choice of measures for the deemed-to-satisfy (DTS) prescriptions were determined through detailed life cycle benefit cost analysis to weigh compliance costs against energy savings. This approach prioritises the efficiency of the building envelope (thermal mass, insulation, glazing and shading) given it typically outlasts changes to services and internal systems. For commercial buildings, compliance can also be achieved using energy simulation to compare with a reference building model (JV3) to give designers some flexibility in trading between different building envelope elements. In the case of residential buildings, the DTS requirements are also hard-coded into the CheNath thermal simulation program. Compliance requires all house designs to meet a minimum level of performance (unconstrained heating and cooling energy) based on the climatic location of the house.

The state of New South Wales is an interesting case in that it requires compliance with the BASIX (Building Sustainability Index) system, which goes beyond Section-J requirements for the building envelope (assessed as thermal comfort) to legislate for reductions in potable water and assess energy efficiency of installed appliances – (air-conditioning system, washing machine, hotwater) and extent of reliance on rainwater collection and on site renewable energy generation. BASIX targets for detached houses require new construction to deliver 40% reduction in potable water consumption and 40% reduction in greenhouse gas emissions compared to the state average consumption of 3,292 kg of CO<sub>2</sub> per person per year. Interestingly the targets for apartments were set at 25% reduction in greenhouse gas emissions as a benefit cost analysis revealed “that unit dwellings have higher per capita greenhouse emissions than houses and were therefore likely to incur significant additional costs to meet a 40% reduction in emissions” NSW Department of Planning, 2011)

### ***Green Star***

Green Star was first introduced to the Australian market in 2003 as a rating system for integrated design of office buildings. Administered by the Green Building Council of Australia, credits in different categories are totalled up achieve 4, 5 and 6 Star building design ratings. It is similar to LEED, sharing the same Intellectual Property and being one of eight national councils which helped to found the World Green Building Council. The rating tools have undergone significant evolution over the years, to encompass more building types such as educational, retail, residential and public and to improve outcomes. There are nine sustainability categories that are rated for Green Star certification: Management, IEQ, Energy, Transport, Water, Materials, Land Use and Ecology, Emissions and Innovation. Currently, there are three Green Star rating tools available, Design & As Built (to certify design & construction), Interiors (to certify interior fit-out), and Communities (to certify plans for precinct level development) that allow developers to ratify projects as they are developed and delivered for occupancy.

A fourth tool Green Star Performance (to certify operational performance), was piloted in 2015 and formally introduced in 2016. Green Star Performance aims to close the loop on performance and allows existing buildings to be rated actual performance against targets for sustainability across similar categories to the As Built Rating tools.

### ***The National Australian Building Environmental Rating Scheme (NABERS)***

Developed in 1999 as the Australian Building Greenhouse Rating (ABGR), the scheme adopted the philosophy that the largest quantum of greenhouse emissions were produced by the existing stock of buildings in developed economies like Australia, and that operational ratings for these buildings were the most effective means of benchmarking and reducing emissions. The rating is “attribute neutral”, and does not consider any design features. Inputs towards the rating process are utility bills, leased area, weekly hours of operations, and a correction for climate (postcode) to benchmark the greenhouse gas emissions (Scope 1 and 2 equivalent CO<sub>2</sub>/m<sup>2</sup>.annum). Subsequently NABERS added Water, Indoor Environmental Quality (IEQ) and Waste benchmarks to its rating suite. The energy and water benchmarks were extended to Shopping Centres and Hotels. Energy benchmarks were also introduced for Data Centres.

The IEQ rating is the most complex and assesses thermal comfort, air quality, acoustic comfort, lighting and office layout through physical measurements for air temperature, mean radiant temperature humidity, air speed ventilation effectiveness, indoor pollutants sound level horizontal light levels and also uses surveys to occupant satisfaction.

## **Outcomes of Rating Tools in Australia**

### ***The role of minimum performance requirements***

Mandatory minimum performance requirements as embedded in the NCC have the best opportunity for capturing the bulk of new building stock; as it is developed or refurbished. In order to operationalise reduction of GHG – the current approach emphasises the thermal performance of the building envelope, rather than to drive innovative approaches with respect to building form, layout, alternate environmental control system or even the extent of reliance on HVAC systems for comfort, or push for an absolute target. Starting from a very low baseline in the early 2000’s, the energy efficiency provisions have served to lift the thermal performance and ensure that all buildings include basic insulation, thermally efficient glazing and comply to a minimum light power density and system efficiency and have served to educate the building industry on these benefits.

Since its introduction, there have been a number of reviews (Pitt and Sherry 2016) based on revised benefit cost ratios arising from lowering of compliance costs thanks to improvements in technology and best practice standards. These included a shift from 5 star level (equivalent to a thermal energy load of 66 MJ/m<sup>2</sup>.annum for Sydney) in 2006 to a 6 star in 2010 (51 MJ/m<sup>2</sup>.annum) for residential and an increase in building envelope stringencies for commercial buildings. Based on our experience in practice, a DTS compliant office building in Sydney is equivalent to a 4 star NABERS rating (193 kgCO<sub>2</sub>/m<sup>2</sup> pa – whole building). However as discussed later in this paper, these levels in themselves are unlikely to lead to deep and significant cuts in greenhouse gas emissions.

In the absence of mandatory reporting of post occupancy emissions it remains difficult to gain proper accounts as to actual savings in energy and greenhouse gas emissions as a consequence of the code. Typically simulation models for compliance use idealised conditions and estimated outcomes are optimistic. Moreover isolation of the NCC regulated attributes (building envelope, installed heating and cooling systems and equipment from

other plug loads during the actual monitoring of houses is incredibly difficult. This is compounded by variation in occupancy (schedule and area) as well as occupant behaviour and appliance efficiency. Even in commercial buildings where more detailed monitoring of end uses is available, our experience suggests that the simulation conducted for purposes of compliance are rarely comparable with the reality of operation.

### ***Incentivisation of the top end buildings through voluntary design based tools***

Since its introduction in 2003, the Green Star tool has been used to rate over 1500 buildings served to embed the conversation around green buildings and sustainability within the major players of the building industry. A large number of developers and building owners use the tool to validate their flagship projects and others committing to achieve minimum 5 Star Green Star – Design & As Built ratings for all new industrial, commercial and retail projects.

The tool is also called up in the design brief of many projects and used by industry as a surrogate for ensuring design quality and environmental design. Its emphasis on the occupant comfort, well-being and broader questions of sustainability as meant that well versed good design practices such as access to views, daylight and increased access to fresh air, used of forest certified timber, low VOCs and no PVC, access to public transport are entrenched in the tool as attributes that can be rewarded with scoreable points. While the Green Star tool adopts fairly ambitious targets under all categories, it allows industry stakeholders to gain credibility for good practice measures even if the ultimate goal is not reached. For example, in the case of greenhouse gas emissions the minimum compliance is set above industry benchmarks at a 4.5 star (equivalent to 164 kg CO<sub>2</sub>/m<sup>2</sup>.annum in Sydney) NABERS equivalent simulated rating with rewards for progressive reduction from this baseline. However, maximum points (20/20) are only achievable for a net zero emissions. This is in contrast to tools such as Living Building Challenge, where compliance requires a pass or fail for the top level target that demands net positive energy and on energy storage for resiliency.

### ***Incentivisation of the top end buildings through Commitment to Performance***

The attribute neutral report cards offered under NABERS prioritises performance and real outcomes. In a science target hungry property market, this has caused a number of assets holders to report their historical operational performance for energy/greenhouse emissions, water consumption, IEQ and waste. Within this framework it must be said that Water and Energy have gained early and wider adoption as these are easy to assess being a single metric, whereas ratings for Indoor Environmental Quality and Waste that require measurement of multiple attributes and include aspects perceived to be intrusive such as occupant surveys are adopted only by a smaller group of buildings.

Table 1: Average reduction in energy intensity over multiple consecutive NABERS Energy star ratings for office buildings (source: NSW Office of Energy and Heritage)

Repeat number of NABERS Energy ratings	Average reduction in energy intensity
2	7%
4	16%
6	24%
8	29%

It can be argued that the requirement to ensure and maintain a minimum, monitored, operational performance for energy/GHG via NABERS, has improved the performance of the stock of office buildings impacted. Table 1 shows the impact of ongoing monitoring where, on average, office buildings captured under the NABERS scheme have been shown to reduce

energy use by 7% on their second rating and 29% by the eighth rating. It is important to note that this is not the performance improvement for a small number of non-representative top performers, but the average improvement of hundreds of buildings in the NABERS database.

The ability to benchmark their asset portfolio over a wider range of categories for sustainability is also gaining traction. The success of Green Star at the top end of the property market (<http://www.architectureanddesign.com.au/news/gbca-ends-the-year-on-a-high-with-80-more-green-st>) where ratings increased from 223 projects in 2015 to 401 in 2016 was attributed to a sharp uptake of the Green Star Performance tool. However at this stage, that tool is in its infancy and its impact in influencing change is not easy to assess as yet.

### ***Policy measures that influence market behaviour and performance***

Figure 1 documents the take up of NABERS Energy (Greenhouse) Star ratings in Australia. There was little uptake until 2003 when the NSW State Government mandated that all their buildings were to be rated for annual performance. Further increases in uptake can be seen in 2006 and 2007 when Federal and then State Governments introduced requirements that buildings owned or leased office spaces be 4.5 stars, and again in 2010 when the Commercial Building Disclosure (CBD) Act requiring all office buildings with more than 2,000 m<sup>2</sup> to report their emissions at the time of lease or sale was introduced by the Commonwealth.

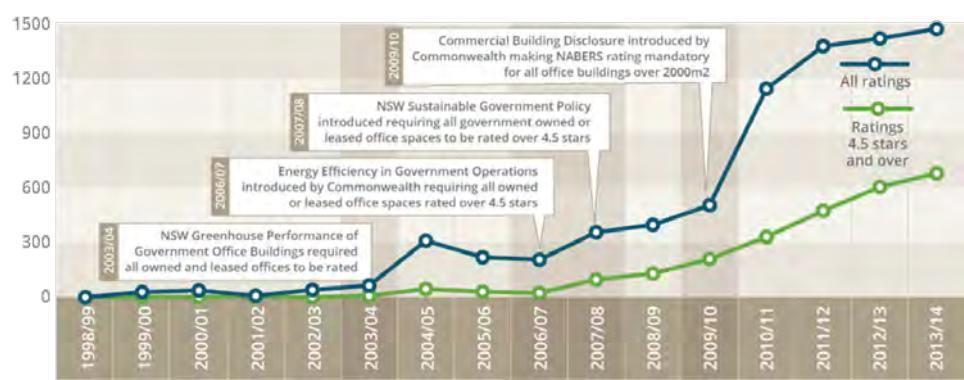


Figure 1: Take up of NABERS Energy Star ratings in Australia

Figure 1 also points to a significant increase in the number of annual ratings at 4.5 star or better after the 2010 CBD Act. This can be traced to a number of factors. The NABERS energy/GHG rating scale originally comprised 5 stars. At the inception of the scheme the top 5 star level, was expected to only ever be achieved by 5% of the target building population. However, once governments mandated a 4.5 star level performance for base buildings (landlord operation equivalent to 87 kg CO<sub>2</sub>/m<sup>2</sup>.annum in Sydney), industry quickly rose to the challenge. By 2010 almost every new building was committing to (and achieving) NABERS Energy 4.5 star, and more than 5% were performing at or above 5 stars (base building equivalent to 71 kg CO<sub>2</sub>/m<sup>2</sup>.annum in Sydney). This led to a review of NABERS Energy benchmarks (RMS and Team Catalyst, 2010) which proposed an extension to the scale to 6 or even 7 stars (net zero). A sixth star was added in 2012. Equivalent to 72 kg CO<sub>2</sub>/m<sup>2</sup>.annum whole building and 35 kg CO<sub>2</sub>/m<sup>2</sup>.annum base building in Sydney, a 6 star level is a 50% reduction in GHG emissions compared to 5 star performance. Adding a seventh star to the NABERS scale offers a ready-made mechanism for zero carbon performance.

Interestingly, Federal and State governments have not reviewed their 4.5 NABERS Energy star performance criterion for the buildings they own or lease. Consequently, the 4.5 star level continues to be the de facto minimum performance standard for all office buildings greater than 2,000m<sup>2</sup> NLA.

### ***Risk and responsibility driving performance, choices and outcomes***

The emphasis on actual performance has resulted in a number of market behaviours.

The speculative nature of the Australian building market contributes to an industry practice that attributes and isolates responsibility for performance to different end users. To accommodate this the NABERS tools offer separate ratings for base building (landlord) and tenancy in addition to whole building ratings (base building+tenancy). However the separate ratings do not portray the full story of the building performance. In the area of IEQ for example, the base building is assessed by measurement of physical attributes of IEQ. Even though the building shell (base building) also has a significant impact on the quality of occupant experience, responsibility of occupant satisfaction ratings for IEQ is isolated only to the tenancy rating. In the case of energy, the base building ratings of many large office buildings and shopping centres do not reflect the energy use of the tenants - for instance many larger stores often run independent HVAC systems separate from the base building.

The Commitment Agreement process is an interesting mechanism established within NABERS to enable developers to market the future performance of the building before commencing construction. It requires the developer to legally commit to achieving a post construction performance target at development application stage. The developer is given a specific time period, usually 18 months after start of normal operation, to have an independent assessor confirm the level of performance. If the committed target is not achieved, a series of mitigation steps may be instigated, following which, all signed up tenants are informed and the non-conformance is reported on a public website.

In a number of building developments we have observed that all cost saving measures, alternate specifications, system configurations are carefully assessed by independent assessors to ensure the commitment agreement is not at risk. As discussed elsewhere (Thomas and Hall, 2004) the goal for a 5 star performance ensured that advanced ventilation system via solar chimneys was not deleted in the face of mid project value engineering in Building A. On the other hand, the push back of capital costs where buildings are developed only to aspirational targets is also noteworthy. In Building B, the use of an HVAC air distribution component designed to improve airflow in low load situations was initially refused by the project manager as it was thrice the cost of the standard product. This was until the electrical contractor realised that installation of this newer device would not require electrical wiring and reheat coils. At this point the displaced capital cost enabled the newer device to be incorporated to capture the GHG savings.

A large number of office buildings are delivered via a design and construct mechanism based around least cost tenders. In our practice, we have observed the risk of demonstrating the initial NABERS Energy performance as per the Commitment Agreement is increasingly being passed onto the head contractor. Legal contracts are being written around "builder retentions", where a percentage of the head contractor fees are retained by the owner/developer until the NABERS Energy star performance is proven within a stipulated time frame.

### **Questions of long term resilience**

The mandatory energy efficiency provisions of the NCC do not go beyond the emphasis on greenhouse gas mitigation to questions of energy sources, or reliance on energy based systems. In the past, the use of simulated performance of heating and cooling was predominantly used as a surrogate measure for the thermal energy load in residential buildings. However, the reality is that more and more residential buildings are actually resorting to air-conditioning for their heating and cooling needs - thanks to increased

expectations for standardised comfort conditions and further compounded by poor designs of apartment buildings where deep plans and poor ventilation make buildings uncomfortable fairly quickly. This situation is further exacerbated during heat waves such as the recent hottest summer of 2016-2017 which resulted in city wide shortages of pedestal fans and air-conditioning units for sale. These aspects further emphasise the need for higher stringency within existing mandatory measures but also highlight the need to ensure aspects such as natural ventilation and passive operability continue to be maintained in residential buildings.

Another area that needs to be tackled is the manner in which the metric for efficiency emphasises unit area meter is masking the total consumption or the consumption per capita of many of these houses (see Thomas and Thomas, 2001) – especially as the average Australia house at over 200m<sup>2</sup> or 90m<sup>2</sup>/person is one of the largest in the world (Wilson, 2014).

In the context of increased potential for energy brownouts and blackouts in the face of extreme weather events and grid stress, measures such as switching off non-essential loads, and/or relaxing comfort tolerances and further attention to on-site generation and storage becomes crucial in both residential and non-residential buildings. Some of these aspects fold into requirements for a Climate Change Adaptation Plan that gains credits under Green Star. While this paper tackles the measures at building level, the opportunities for precinct wide strategies in this respect are gaining attention through tools such as Green Star Communities.

Most non-residential buildings are designed to very narrow temperature conditions (20-24°C) which reinforces the assumption of year round air-conditioning. Under normal conditions, targets for 4.5 and 5 star performance are routinely achieved using energy efficient buildings that are sealed and air-conditioned all year round. Under current rating tools, moving performance of such buildings towards zero carbon could be achieved through a techno-centric focus through huge arrays of PV panels. However a more cost effective and arguably resilient approach could come from a philosophical shift to building comfort that questions standard reliance on year round air-conditioning, and seeks to reinstate mixed mode conditioning through spatial and temporal diversity in buildings (Thomas, 2107).

### **Conclusions – A regulatory pathway towards zero carbon**

As discussed in this paper, Australia has seen a number of effective regulatory and voluntary initiatives to improve the sustainability of buildings with particular emphasis to mitigate greenhouse gas emissions in the past decade. These tools have been primarily developed to influence and work with market forces, and have brought these questions to the front and centre of building practice. The findings above demonstrate the value of setting aspirational targets within Green Star and the value of setting operational targets that are annually assessed under the Commitment Agreement protocols of NABERS to shift the performance of the office building sector. Furthermore as discussed, the use of design ratings and commitment agreements have encouraged the market to mature and rise to the challenge and actually deliver buildings to meet ambitious targets.

However in terms of new buildings, the only regulatory framework that covers GHG of ALL buildings is the NCC. We argue that currently the NCC is not stringent enough and remains a market oriented framework where planetary costs are not driving the stringency limits. In contrast, if we consider these from the perspective of keeping Australia's commitments to get to no more than 2 degree global warming by 2050, as discussed above, we need to halve our emissions every decade and get to zero carbon in three decades (Rockström et al, 2017). While this is in keeping with the commitments of three of the states (NSW Victoria and South Australia), in the country, buildings will need to play their part.

In the case of new commercial buildings we contend that the mandatory target for all buildings (not just government owned or leased) would need to rise from 4.5 star NABERS to 5 star in the next decade and then to the 6 star level in the following decade and zero carbon in the decade after. Such deep cuts and commitments to actual performance would need to extend beyond office buildings to include retail, industrial buildings, and mandate whole building ratings rather than only base-building or tenancy ratings to ensure no potentials for mitigating GHG are lost. The relatively lenient energy targets in the residential sector must also shift towards zero carbon emissions by 2050 especially in multi residential apartment buildings, given the increase in the construction of apartment buildings coupled with the concerns for resilience of such buildings as discussed above. Similar to commercial buildings, these should include some mechanism for commitment operational performance between the developer/contractor and tenant association.

The bulk of the buildings that will exist in 2050 are already with us. Increasing heatwaves are causing a sharp uptake of air-conditioning over summer and exacerbating energy use in these existing buildings - an aspect that is completely escaping the attention of the building monitoring or regulations in place. Based on the success of the building disclosure in office buildings (CBD), we recommend that similar schemes to reveal and document actual performance need to be mandated for all existing building types, in conjunction with incentives to retrofit and improve performance.

The regulatory frameworks and ratings tools in Australia offer the necessary mechanisms to bring about the change. That said, increased stringencies and significantly more ambitious targets and a commitment to performance rating is required to ensure buildings play their role in meeting the Paris 2C GHG emission reduction targets.

## References

- Rockström J., Gaffney O., Rogelj J., Meinshausen M., Nakicenovic N., Schellnhuber H.J., Science, A roadmap to rapid decarbonisation, 24 Mar 2017, Vol. 355, Issue 6331, pp. 1269-1271
- U.S. EPA. 2008, Inventory of U.S. Greenhouse Gases Emissions and Sinks: 1990-2006, p. ES8.
- ABCB (Australian Building Codes Board) 2016, National Construction Code (NCC) Vol 1, Section-J Energy Efficiency, and Vol 2, Section 2, Part 2.6; (downloadable at <http://www.abcb.gov.au/Resources/NCC>)
- IPCC 2007. Climate Change 2007 Synthesis Report, p. 59.
- GBCA (Green Building Council of Australia), Green Star Ratings, [gbc.org.au/green-star/](http://gbc.org.au/green-star/)
- OEH (NSW Office of Environment and Heritage), [nabers.com.au](http://nabers.com.au)
- NSW Planning and Environment, 2004, BASIX, Building Sustainability Index, [www.planningportal.nsw.gov.au/planning-tools/basix](http://www.planningportal.nsw.gov.au/planning-tools/basix)
- Pitt & Sherry, 10 May 2016, Pathway to 2020 for Increased Stringency in New Building Energy Efficiency Standards: Benefit Cost Analysis: Commercial Buildings: 2016 Update
- Thomas, L.E. & Hall, M.R. 2004, 'Implementing ESD in Architectural Practice - An investigation of effective design Strategies and Environmental Outcomes', Proc. PLEA Conference, Technische Universiteit Eindhoven, Netherlands, pp. 415-420.
- Thomas, L.E. 2017, 'Combating overheating: mixed-mode conditioning for workplace comfort', Building Research and Information, vol. 45, no. 1-2, pp. 176-194.
- Thomas, P.C., Venkatesan, A. & Thomas, L.E. 2014, 'Effective natural ventilation in modern apartment buildings', Proc. 30th International PLEA Conference, CEPT UNIVERSITY PRESS, Ahmedabad, India, pp. 353-360.
- Thomas, L.E. and Thomas PC 2000, 'A Study of an Energy Consumption Index Normalised for Area in House Energy Rating Schemes', 38th Annual Conference of the Australian and New Zealand Solar Energy Society Resource Management Solutions and Team Catalyst, 2008, Review of Benchmarks, Australian Building Greenhouse Rating, for NSW Dept of Environment and Climate Change
- Wilson, L. How big is a house? Average house size by country, [shrinkthatfootprint.com/how-big-is-a-house#wXGCmEpDXBfdlb4s.99](http://shrinkthatfootprint.com/how-big-is-a-house#wXGCmEpDXBfdlb4s.99)



# PLEA 2017 EDINBURGH

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## **`Learning from 'horror' stories: a plan of work to reduce the performance gap in deep retrofit**

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**Abstract:** Over the past 20 years efforts have been made to bridge the performance gap by developing design guidance and reports to raise awareness and increase construction quality of the delivery and handover stages; as well as improving tools and prediction methods by validating them with real data comparing anticipated performance with achieved energy use. The complexity of the gap ‘problem’ increases in deep, low-carbon refurbishment processes. Both the scale and quality of construction work need to be increased if challenging emission reduction targets are to be met. Established professional work plan frameworks (e.g. RIBA and Soft Landings) have been designed mainly with new build in mind without explicitly capturing important stages of a retrofit project that close the loop from in-use to design and back to in-use. The Appraisal (or Strategic) stage misses important diagnostic actions for evaluating client/occupant past experience and assessing existing building energy performance and Indoor Environmental Quality. Similarly although Project roles are described, they do not include the skills/knowledge that individuals (or teams) need; or the tools/ methods that can be used to manage and reduce unforeseen risks related to the existing building condition. This paper presents a modified version of the RIBA Plan of Work, which shows existing and additional workstages for deep refurbishments in a continuous cycle, linking roles to skills, knowledge and tools. Drawing upon evidence from pioneering empirical studies in deep refurbishment in the UK, the notion of ‘failures’ and key lessons from previous ‘horror’ and ‘learning’ retrofitting stories are used here to highlight problems and risks in each of the proposed work stages; and to address the major changes needed in traditional processes to reduce the retrofit performance gap.

**Keywords:** performance gap, domestic retrofit, deep refurbishment, low-carbon technologies, skills and knowledge

### **Introduction**

It has long been recognised by both industry and policymakers that buildings are not only the most significant consumers of energy but they also represent the largest untapped potential for energy savings and reductions in greenhouse gas emissions. There were 28.1 million homes in the UK in 2014 (ONS 2016) at least 87% (over 24 million) of these will still be standing and be in use by 2050 (Power, 2008). The 1% of new build added yearly into the existing stock is small percentage compared to the 99% of buildings that are already built and are responsible for over a quarter of all UK carbon emissions (Power, 2008). However, in the UK under current policies, CO<sub>2</sub> emissions from buildings by 2030 are estimated to be

reduced only by 12% below the business as usual levels, and not the 30% targeted (Galvin and Sunikka-Blank, 2017).

Energy policy debates emphasise the physical, technical and economic side of building retrofits, formulating ‘hero stories’ of works that individuals have undertaken to achieve success (Janda and Topouzi, 2015). These stories, and their content, rely on modelling technical potential rather than understanding the actual social capacity to support change that is held in collaborative professional practices, knowledge and skills. In buildings the performance gap - between what energy-efficiency design standards and modelling promise to deliver and what happens in practice - also rests on the different types of the stories that can be told, and the ways such stories are communicated to different actors (e.g. policy makers to building industry, design team to users, construction team to clients). Previous work by Janda and Topouzi (2015) identifies three different type of stories: hero stories, learning stories and horror stories, describing how different types of narratives in energy storytelling may encompass different qualities of reality, fiction and interpretation, either creating policy gaps or helping to solve them. ‘Hero’ stories are taking place in the ‘imaginary’ world of estimates and forecasts while the ‘learning’ and ‘horror’ stories are in the real world. Energy hero stories in building retrofit take place in non-ideal existing environments so that, although experiencing difficulties during the process, there is always positive heroic input to achieve (or transcend) design performance targets. ‘Learning’ stories lie between the technical potential and what is achieved in practice. The narrative of a retrofit learning story is what the diagnosis of existing building condition and the experience of commissioning tell us, and what the post-construction reality checks and post-occupancy monitoring reveals. Janda and Topouzi (2015), in examining the implications of storytelling in energy policies, suggest that every hero story has at least one learning story in it (or associated with it). When the surface of the hero story is scratched then the learning story can be uncovered. In this transition from ‘hero’ to learning story there is also an intermediate stage of something ‘failing’ in practice, - this is the ‘horror’ story.

In this paper ‘hero’ stories are deliberately not discussed, as the ‘hero’ in these narratives tends to be a technology or a set of technologies rather than the person or group providing them (Janda and Topouzi, 2015). The main focus here is on the intermediate set of narratives that involve a story of failure, fear of failure or risk of failure, of technologies that did not perform as promised or processes that did not occur as planned (e.g. InstituteforSustainability, 2012a, InstituteforSustainability, 2012b, Gupta et al., 2015, Fedoruk et al., 2015). Adding a learning story to the hero story and turning the ‘failure’ into an educational opportunity with broader possible outcomes means that ‘horror’ tales from the real world start to be told. In retrofitting existing buildings there is an unseen presence of risks and failures that are not apparent until works have started. The “plan of work” proposed in this paper looks the complex socio-technical system – building retrofit – and the relationships between people, stages, roles and skills, rather than simplifying it to a technical-only system.

### **Performance gap in low-carbon retrofits**

Previous studies explored performance gap discrepancies focusing on technical and non-technical factors related to: thermal performance of the building fabric, energy performance of the services, occupancy and operation. From a technical perspective a considerable number of studies investigated the mismatch between design, construction and operation, looking at how people use design tools, computer models, certificates and monitoring

techniques. This paper explores the performance gap issues as they evolve within the retrofit process work stages in different housing sectors (social and private owned). Our analysis uses evidence from large scale retrofit projects, pioneering housing retrofit networks in the UK and 'grey' literature (e.g. EST, 2007, NEF, 2014, ZeroCarbonHub, 2014a, ZeroCarbonHub, 2014b, Fawcett and Killip, 2014, Dollard and Edwards, 2015, Dollard and Edwards, 2016, Topouzi, 2015). A review explored established Plan of Work frameworks like Royal Institution of British Architects (RIBA) and how such frameworks are used in retrofits and how they are used by different actors. The paper draws out a retrofit-specific Plan of Work, adapting the RIBA procedure. It discusses how non-technical horror story causes of the design-performance gap (lack of technical knowledge; poor communication among project teams; unclear boundaries or roles and responsibilities) within different workstages emerge and what role the proposed feedback loops in the plan can play.

### Retrofit process and plan of work frameworks

For over a half century in the UK, the Royal Institute of British Architects (RIBA) Plan of Work has been the model building design and construction process providing a framework for organising and managing building projects for both new and existing buildings (RIBA, 2013). It is a process map and a management tool that organises important processes in a building project of briefing, designing, constructing, maintaining and operating. In 2012, the Government Soft Landing policy was driven by the UK Government Construction Board as an opportunity to incorporate principles of the Soft Landings framework (SLF) (2009) for both new construction and refurbishment. An integration of the RIBA work stages and SLF project key activities are summarised in the latest version Soft Landings and Government Soft Landings (BSRIA, 2015). A major strength of this integration for a retrofit project is that it underlines important procedures to progress a project in a rationalised and structured order from commencement to completion and beyond. However, these frameworks are mainly designed with new build in mind and are not detailed or aligned with the tasks, objectives and key issues encountered in a retrofit process. Four specific issues can be identified where the RIBA Plan of Work does not align well with the nature of retrofit projects:

- Missing important diagnostic actions for evaluating client/occupant past experience and assessing existing building energy performance and indoor environmental quality;
- Overlooking differences in the types of retrofits (deep, typical, shallow) and size (individual or repeated/area-based);
- Usability considerations from different actors (e.g. design teams, homeowner or builders);
- Lacking guidance on the tools and methods that can be used to manage and reduce unforeseen risks or the skills/knowledge different roles need to for retrofitting existing buildings.

All four of these are related to the fact that a retrofit project starts with a building in use rather than a blank building site. The design and construction process needs to negotiate a loop from an initial 'in-use' condition into a design phase, and then round to 'in-use' again.

## **Horror and learning stories**

Drawing upon the evidence from academic and grey literature review, and given the abundance of 'hero' stories, this paper explores the underplayed and less told 'horror' and 'learning' stories. Accepting that learning stories occur in the 'real world' (Janda and Topouzi, 2015, table 1, p.528) of construction and, post-construction, of use of the building when it is occupied, this section gives examples of the source and causes of these two types of stories.

### ***Retrofit 'Horror' stories***

Evidence suggests that the cause of 'horror' stories often arises from a lack of technical knowledge, poor communication and unclear boundaries of roles and responsibilities that generally occur during four main stages: preparation/appraisal, design/specification, construction/ delivery and in-use/ maintenance. Much of the discussion that follows has to do with the relationship of these causes in the 'real' world.

#### *HS1 Lack of technical knowledge and skills*

Evaluation of an existing building's energy performance requires a combination of three things: theoretical knowledge of applied building physics (e.g. the relationship between temperature and relative humidity), skills in design and construction; and skills in understanding the interaction of buildings and their users. In many cases the tools used to diagnose the existing situation of technical and in-use performance do not reveal the full story. For instance, Energy Performance Certificate assessments may offer a technical estimate of the energy performance based on assumptions about the impact of individual building elements on performance. However, these impact calculations are dependent on non-technical issues that are either based on standardised assumptions about occupancy, heating patterns or not even considered (like control and usage). It is a story of failure, of the inadequacy of the tools that are used as a result of the lack of knowledge and skills in Post Occupancy Evaluation (POE) and Building Performance Evaluation. In this case, the risk is of the central character (client, occupant or builder) being unable to deal with a real project and deciding to leave requirements unsatisfied (or partly satisfied). This in turn leads to risks for policy-makers as they contemplate possible interventions in retrofit markets. Over the life-time of a building the different retrofit interventions (deep or shallow) need to be seen as a hybrid of old and new materials/technologies; and old and new skills (Chan and Dainty 2007, p378), that need to be evaluated and evolve over time under a 'whole-house' perspective. As Fedoruk et al. (2015) put it: "knowing what works and where the big risks lie so that care and attention are paid to the things that make a big difference to the outcome" (performance).

#### *HS2 Poor communication*

In this arena, most horror stories are between the design and construction stages; and between handover and use. The complexity of deep refurbishment projects inevitably involves unpredictable issues appearing as work progresses. This is the time when the imaginary world of design aspirations (e.g. standardised 'one solution fits all', complicated modelling solutions lacking technical details, design for a default user disregarding occupants' lifestyles) meets the real world and there is a need for communication between multiple actors (client, design and construction teams). It is a story of failure when high cost, low-carbon specified technologies did not perform as promised because of insufficient

ways to communicate to the users all aspects of a retrofit process. For instance, at the pre-refurbishment stage, not entirely explaining design target/standards and design options; low-carbon measures and technologies; as well as the project timeline. At the post-refurbishment stage, not providing personalised information; not providing training by a knowledgeable demonstrator for the specific combined and individual systems, at a time appropriate for the user; and not ensuring aftercare support. Communication problems prevent the creation of feedback loops which would allow individuals and teams to accumulate experience of ‘failure narratives’ from different actors and stages. Such failure narratives may be technological (e.g. a system with a CHP boiler, solar thermal collector and no integrated control system). Alternatively, the failure may be more socio-technical (e.g. a lack of handover and user training leading to the risk of inefficient operational practices).

### *HS3 Unclear boundaries for roles and responsibilities*

Low-carbon standards and combined systems require coordination and collaboration between professional groups (e.g. architects, engineers, energy consultants, constructors, builders, technicians). The horror story emerging from the construction and handover stages is when members from these groups play their part without taking responsibility for the whole-house energy performance targets. Taking responsibility would involve practices like reality checks in the delivery/handover stage that test the performance of the building-system as a whole, rather than testing the performance of individual measures, allocated by individual trade responsibilities. Taking part or full responsibility for integrated solutions is widely seen as a risky thing to do, precisely because it relies on others playing their part fully and competently. For roles and responsibilities to be clear, there needs to be an overarching role for team and project management, which is typically not present. Such coordination is crucial for retrofit at many levels: for on-site problem solving; to intervening in crucial environmental and energy decisions; to identifying and communicating issues of misalignment between design intent and implementation. In certain types of projects when managing design in construction, there is a distinct separation of ‘doing’ from ‘managing’ (as Gray et al. (1994) cited in Hughes and Murdoch, 2001, p13), as is often followed by horror stories.

### **Proposed work plan**

The Plan of Work proposed by this paper integrates additional stages into the existing BSRIA (2014), (BSRIA, 2015) framework. These additional stages are , developed explicitly for retrofits, creating a continuous cycle with feedback loops between stages (Figure 1 below). The scope of this work plan is to bring together key issues related to different roles and responsibilities, communication and tools in order to enable horror stories provide a learning outcome. The continuous cycle of retrofit stages ‘begins’ and ‘ends’ in the ‘real’ world with the appraisal of existing condition through to the repair and maintenance. Within this cycle only the four stages (stage1 to 4) of design occur in the ‘imaginary’ world.

Figure 1 illustrates the main connections provided by twelve feedback loops. Each of these loops between stages can be repeated several times during the retrofit process to accumulate implementation outputs and to phase out fear.

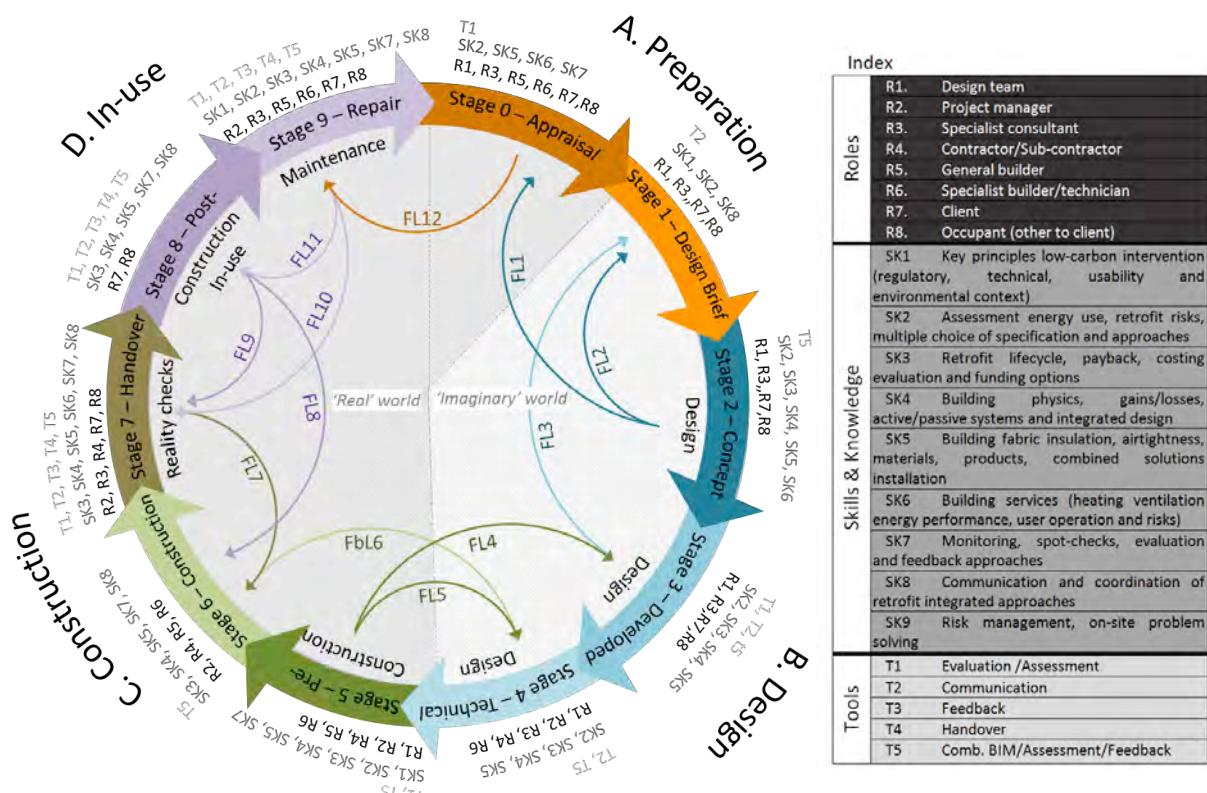


Figure 1. Proposed outline of main work stages in a retrofit process and feedback loops (FL) (based on sources (RIBA 2013, BSRIA 2014), related to roles, skills and knowledge, and tools.

### Retrofit ‘Learning stories’

To reduce the distance between imaginary world (design intent) and real world (construction/in-use) (Janda and Topouzi, 2015), more learning stories need to be added in the energy toolkit to move beyond binary hero-horror or success/failure frames. The proposed work of plan in this paper aims to bridge the gaps that the transition between the two ‘worlds’ (imaginary and real) creates. Away from the individualistic perspective of hero stories the horror/learning stories aim to transform existing systems in retrofit process. The feedback loop is used as a tool to turn the causes of horror stories (lack of knowledge and skills; poor communication; and unclear roles and responsibilities) into accumulated learnings. These causes can be found in all stages and in different practices during a retrofit process. Here the discourse in the following examples is of feedback loops and learning outcomes in relation to the horror stories as discussed earlier.

**Feedback Loop 1 (FL1) and HS1:** FL1 is the only feedback loop in the proposed circle which allows design aspirations, evaluation frameworks and monitoring performance techniques from the ‘imaginary’ world can be explored in the ‘real’ world; while insights and learning capacities from the real world back can also feedback to inform the design. The technical skills and knowledge of building performance evaluation become an in-situ exercise for the design team, evaluator or builder, to explore not only technical issues but include the overlooked occupancy and usage related factors. Feedback Loop 4 (FL4) and HS2: The complexity of retrofit projects makes the use of design practices and heuristics based on previous learning and experience with low carbon-standards and systems unavoidable. The loops from pre-construction to developed design can help the design team, the construction teams and clients to re-evaluate and inform often overoptimistic design aspirations. This

loop allows problem-solving to be communicated to (and amongst) different actors (designers, contractors and users), using frequent reviews of design-build problems at early stage before problems become irreversible and cannot be treated. This review is the learning of which options are not realistic on site for the specific property and users, information which can help shape other design stages and transmitting learning between projects.

**Feedback Loop 8 (FL8) and HS3:** A feedback loop between the post-construction/in-use and handover/reality checks can offer continuity in roles and responsibilities to single people or teams at a crucial stage of delivery where users are often left with no aftercare support. The learning process in this loop evaluates the implementation of the technical and non-technical issues and the performance outcome of the building system as a whole beyond individual perspectives, using instead an evaluation of a collective team work. Finding causes of misalignment between construction and in-use can help to reduce the gap between ‘doing’ and ‘managing’ and to define the roles that roles and responsibilities for the next stages of repair and maintenance.

## Conclusions

Undertaking deep retrofit of existing buildings requires a major shift in how design teams, constructions teams and users share information and knowledge in order to achieve consistently high quality, low carbon outcomes. From a ‘constructive pessimism’ starting point, learning stories bring up the contingencies of things that are not going to work as expected and planned. This paper proposes a cyclical work-plan for retrofits, developed from the accepted industry standard framework and tested by RIBA over decades, which codifies feedback loops in order to support this concept this and change from assessing individual measures to evaluating whole building system performance. Critical to achieving this transformation is the need to cross boundaries – the boundaries between professions, the boundaries between the design, construction and use, boundaries between building components.

In exploring how to blur the boundary between the imagined world of design and the real world of construction and use, we identify how narratives play a vital role in how individuals and teams develop understanding of their project experience. While technology-focussed ‘hero stories’ of individuals battling against the odds appear to dominate much of the discussion in energy policy and practice, we argue that paying attention to ‘horror stories’, and the fears that such horror stories are founded upon, actually help to identify the positive ‘learning stories’ that could, if routinely discussed and shared, increase the capacity of the construction industry to deliver deep retrofit at the pace and scale required.

The proposed revision to the RIBA Plan of Work explores the transition between stages from ‘imaginary world’ to ‘real world’, looking the causes of horror stories from lack of technical knowledge, poor communication and unclear boundaries of roles and responsibilities within each of these. It highlights a new task – that of appraising an existing building in use, which requires technical and socio-technical understanding. This has far-reaching implications for education and training in construction. Equally, the feedback loops identified in Figure 1 make new connections between not just stages of design, but also between the design and construction phases of a project. If these connections are to be made in a systematic way, the education of design professionals and construction trades will need to be more closely aligned, with insights from each group being respected and

taken on board by the other. Integrating feedback loop mechanisms during a building's lifecycle can increase significantly the continuity of a learning process. Such a joined-up approach may be a long way challenging for current practices, but it is badly needed if learning stories are to be heeded and climate change targets are to be met.

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### References

- BSRIA 2014. The Soft Landings framework for better briefing, design, handover and building performance in-use. <http://usablebuildings.co.uk>.
- BSRIA 2015. Soft Landings and Government Soft Landings: A Convergence Guide for Construction Projects. In: BSRIA (ed.). BSRIA: BSRIA.
- DOLLARD, T. & EDWARDS, T. P. 2015. Builders' Book. In: HUB, Z. C. (ed.) *Zero Carbon Hub*. Zero Carbon Hub.
- DOLLARD, T. & EDWARDS, T. P. 2016. Services Guide. In: HUB, Z. C. (ed.) *Zero Carbon Hub*. Zero Carbon Hub.
- EST 2007. CE83 energy-efficient refurbishment of existing housing. In: TRUST, E. S. (ed.). London: Energy Saving Trust.
- FAWCETT, T. & KILLIP, G. 2014. Anatomy of low carbon retrofits: evidence from owner-occupied Superhomes. *Building Research & Information*, 42, 434-445.
- FEDORUK, L. E., COLE, R. J., ROBINSON, J. B. & CAYUELA, A. 2015. Learning from failure: understanding the anticipated–achieved building energy performance gap. *Building Research & Information*, 1-15.
- GALVIN, R. & SUNIKKA-BLANK, M. 2017. Ten questions concerning sustainable domestic thermal retrofit policy research. *Building and Environment*.
- GUPTA, R., GREGG, M., PASSMORE, S. & STEVENS, G. 2015. Intent and outcomes from the Retrofit for the Future programme: key lessons. *Building Research & Information*, 43, 435-451.
- HUGHES, W. & MURDOCH, J. 2001. Roles in construction projects: Analysis & Terminology. A Research Report undertaken for the Joint Contracts Tribunal Limited: University of Reading.
- INSTITUTEFORSTAINABILITY 2012a. Occupant-centred retrofit: engagement and communication.
- INSTITUTEFORSTAINABILITY 2012b. Retrofit insights:perspectives for an emerging industry. Key Findings: Analysis of a selection of Retrofit for the Future projects. UCL.
- JANDA, K. B. & TOPOUZI, M. 2015. Telling tales: using stories to remake energy policy. *Building Research & Information*, 43, 516-533.
- NEF 2014. Breaking barriers: An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan  
SummaryReport.pdf. In: FOUNDATION, N. E. (ed.). Retrieved from: [http://www.nef.org.uk/themes/site\\_themes/agile\\_records/images/uploads/BreakingBarriers\\_SummaryReport.pdf](http://www.nef.org.uk/themes/site_themes/agile_records/images/uploads/BreakingBarriers_SummaryReport.pdf).
- POWER, A. 2008. Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? *Energy Policy*, 36, 4487-4501.
- RIBA 2013. RIBA Plan of Work 2013 Overview. In: SINCLAIR, D. (ed.). 66 Portland Place, London, W1B 1AD: RIBA.
- TOPOUZI, M. 2015. *Occupants' interaction with low-carbon retrofitted homes and its impact on energy use*. DPhil DPhil, University of Oxford.
- ZEROCARBONHUB 2014a. Closing the gap between design and as-built performance. Zero Carbon Hub.
- ZEROCARBONHUB 2014b. Closing the gap between design and as-built performance: Evidence review report.



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*Design to Thrive*

## Zero-Energy Me - The Struggle for Individual Energy Neutrality

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**Abstract:** The strife for zero-energy buildings and carbon-neutral developments is – however noble and benevolent – mostly aimed at an abstract target, such as a design in architecture school, a house still to be built, an urban plan under development. It is mostly dealing with there, then and them, rather than here, now and us. A sustainable, climate-, carbon- or energy-neutral society implies that each individual needs to be sustainable, climate- or carbon-neutral. Acknowledging this, the main author started to keep track of his performance in energy use, travel and food habits, and during lectures he presented about this openly to his students. Over a period of 7 years, the detailed tracking of energy, travel and food, and, more so, consecutive actions taken, have led to a lower energy consumption and hence carbon footprint. In the author's private life, we should say, because in the meantime his professional international career took off and so had many flights across the globe. They once more demonstrated that we, even when living low-carbon consciously, often are penny-wise, pound-foolish. This individual research clarified the greatest challenges and most effective strategies of living in a modern, dense city, with abundant access to unsustainable food and with easy opportunities to travel unsustainably for little money. As it held a mirror to the author, it will do too to a greater audience.

**Keywords:** net zero-energy, carbon neutrality, accommodation, transportation, food

### Introduction

If we want to stay beneath a 2-degrees temperature increase – widely considered a maximum level to avoid runaway climate change with unpredictable outcome - the world needs to reduce its carbon emissions by 80% in the year 2050 [IPCC 2014]. For a sustainable situation on the longer term, climate neutrality or carbon neutrality is essential, creating a balance between the greenhouse gases emitted on the one hand and chemically binding or sequestering of these gases on the other.

### Society's great energy challenge

The predominant part of achieving this goal, as agreed upon in the Paris treaty of 2015, is to be achieved by becoming independent from fossil fuels, the greatest contributor to greenhouse gases as methane, CO<sub>2</sub> and NOx. Therefore, the term 'fossil free' was introduced in various European projects already since 2006 [e.g. Roggema et al. 2011], after Al Gore's 'An Inconvenient Truth' came out [Gore 2006]. Fossil free simply means that no fossil fuels (coal, mineral oil and natural gas) are used anywhere in the system considered. With our fossil society this is an ambitious goal to achieve, and it may take a lot of time to get there. In the meantime, becoming 'net zero-energy' already is a big step. This ambition, often also described as 'energy-neutral', means that in a year's time one is not to use more energy than one can generate oneself. It implies acceptance of fossil fuels as long as this quantity of energy

is compensated for by self-generated renewable energy. In its Energy Performance for Buildings Decree (EPBD), the EU prescribes that as of 2020 all new buildings need to be ‘nearly zero-energy’. The word ‘nearly’ of course leaves space for interpretation, but it is clear that designing fully zero-energy buildings will put architects on the safe side for a building permit.

### ***Individual energy-neutrality***

The strife for zero-energy buildings and carbon-neutral development is noble and benevolent for future generations to follow. However, it is usually aimed at an abstract target, such as the design of a building in architecture school, a house still to be built, an urban plan under development. It is mostly dealing with there, then and them, rather than here, now and us. A sustainable, energy- or carbon-neutral society will not be possible if people themselves on average are not sustainable, climate-adaptive, carbon-neutral in their own way of living. It is easy to point at others and not achieving these goals oneself. People who understand the importance of striving for a sustainable world, must set the example by becoming net zero-energy in their habits. Acknowledging this, the main author started to keep track of his performance in energy use, and during lectures he presented about this openly to his students. This paper gives an account for the measurements and calculations done in the period of 2010-2016.

### **Boundary conditions and starting-points**

#### ***Sources of energy use considered and unconsidered***

Energy neutrality may be considered for many parts of our lives.

Perhaps most trivial is the energy used at home, including building-related energy (for lighting, heating, ventilation, pumps etc.), user-related energy (for use of equipment, devices, lifts etc.), and also the ‘embodied energy’ of building materials (for winning, transport, production etc.). The latter we usually do not consider because we usually do not have data thereof.

Other forms of energy use are related to our own living: mobility (private travel, commuter travel etc.), water (energy needed for producing drinking water, for pumps, for the purification of waste water, etc.), food (energy needed for growth, transport, storage and production of food), clothes (energy needed for the resources, transport and production of clothes), stuff (energy needed for the resources, transport and production of stuff), and again, the embodied energy of packaging and materials of previous products.

Least obvious, yet an essential part of everyone’s life is the (embodied) energy use of everything we use outside ourselves: infrastructure (roads, bridges, piping, wiring, sewage, etc.), utilities and facilities (for electricity, drinking water, waste water treatment, etc.), public objects (public buildings, street furniture, etc.), commercial objects (factories, offices, retail, etc.), and so on.

For practical reasons this research was limited to the building-related and user-related energy at home, mobility and food. Based on estimates that around 30-40% of carbon emissions result from the built environment (buildings) and 20-30% from transportation, the authors assume that thereby they have covered over half the energy individuals use, at least a part they can influence.

## **Method**

Over a period of 7 years the main author's energy use and travel was tracked in detail, linked to annual energy bills. Since the main author moved house in December 2009, with a baseline measurement done, account was made on the 1<sup>st</sup> of January every year. 2010 was the reference year, with little to no adjustments made to the house, after which various consecutive measures were taken and their effect measured.

Next to this private part of life, a professional career defines the use of energy; also with the individual considered. Working in an office most of the time, the energy consumed at the office is important but has to be divided by all who use it. Business travel can be an even more decisive factor. In the case of the authors this is certainly true, reason for which to keep track of business trips, both by car, train and plane.

## **Basics of energy**

Repetition of some figures is useful before we present energy data in the section to come. For conversion to a general energy value only two conversion factors are relevant (actually only one): 1 kWh = 3.6 MJ; and 1 MJ = 0.278 kWh. Besides, the energy content of common energy sources is important. Table 1 gives an overview of this. Notice that all fossil fuels as well as biotic oil and fat have an energy content of around 36 MJ i.e. 10 kWh per unit.

Table 1. Energy sources and energy content per unit

<b>Energy source</b>	<b>Unit</b>	<b>Energy content</b>	
Natural gas	1 m <sup>3</sup> nge (natural gas equivalent)	35.2 MJ	9.8 kWh
Petrol	1 l (litre)	32.4 MJ	9.0 kWh
Diesel	1 l	35.8 MJ	10.0 kWh
Kerosine	1 l	37.4 MJ	10.4 kWh
Oil and fat	1 kg vegetable/animal	37.0 MJ	10.3 kWh
LPG	1 m <sup>3</sup>	26.0 MJ	7.2 kWh
Coal	1 kg	24.0 MJ	6.7 kWh

Related to the energy mix of electricity the Netherlands has an average efficiency of around 45%, which implies – unless one uses electricity from renewable sources – we have to multiply the use of electricity by 2.2, in order to get to the amount of primary energy.

Furthermore, note that one flame (either a flame of a candle, oil lamp or gas burner) has a heat power of around 100 W [Hermans 2011]. Gas boilers and geysers often used to have ten rows of ten gas flames, giving them a heat power of 10 kW. One flame burning one hour long has produced  $100 \times 1 = 100$  Wh (watt-hour). Someone taking a shower for 15 minutes has used  $10,000 \times 0.25 = 2,500$  Wh or 2.5 kWh. Taking an efficiency of 100%, this is the equivalent of 0.25 m<sup>3</sup> of gas, or 250 ml ('a longdrink glass') of petrol.

## **Local energy habits**

In the Netherlands, the main author's home country, inhabitants typically have access to electricity, natural gas, drinking water, sewage, and other utilities that are centrally provided by public or private service companies. Recently, there is a shift towards dwellings free of natural gas, but the large majority of the building stock still relies on it (for both heating and hot water). Cars mostly use petrol or diesel, and airplanes kerosene. Electricity comes from centralised, regional power plants, which run on natural gas, coal or a small share of biomass. In North-Western Europe electricity is not bound to country borders and some of the energy produced in the Netherlands is exported while a small amount of nuclear power is imported from Belgium or France. The Netherlands are positioned second to last on the European table

of renewable energy (a share of around 5%) [Eurostat 2016]. So the energy mix is diverse, with dominance of natural gas.

### ***Energy use of Dutch households***

For their house, Dutch households on average use 1,400 m<sup>3</sup> of gas (13.6 MWh thermal) and 3,500 kWh (7.7 MWh of primary energy). In total this is 21.3 MWh<sub>prim</sub> (76.7 GJ). Ignoring public transport and bikes, for their mobility the Dutch drive on average 13,300 km per year. With 8 l/100 km this is around a thousand litre of diesel or petrol, or 36 GJ or 10 MWh<sub>prim</sub>. Hence, for living and private travel the total energy demand of a Dutch household is 31.3 MWh<sub>prim</sub>. Households on average contain 2.2 persons [CBS], so the individual energy use is 14.2 MWh<sub>prim</sub>. This is nearly 30% of the total energy the Netherlands used in the year 2015: 49.9 MWh per inhabitant [PBL 2017]. The private use of energy requires a continuous power of 3.56 kW, of which 2.43 kW for the house.

### **Domestic energy consumption**

#### ***Energy system of the house***

The terraced house under scrutiny is positioned in the inner-city of Delft, the Netherlands. Officially it is an apartment, squeezed in between two neighbours and a cinema at the back, with shops underneath and a parking garage below these. It therefore has an uncommon wide and shallow floor plan, with one open façade. Total gross floor area is 165 m<sup>2</sup>, with approximately 460 m<sup>3</sup> of space. The house is inhabited by a family of four: two parents and two teenage children.

The multifunctional urban complex the house is part of was delivered in 2005. Compliant with the energy codes of that time it has HR+/HR++ windows ( $U = 1.0\text{-}1.3 \text{ W/m}^2\text{K}$ ) and, compared to the Dutch average, good thermal insulation ( $R_c = 3.0 \text{ m}^2\text{K/W}$ ). For energy-efficient ventilation the house has so-called balanced ventilation with heat recovery, which can be switched to three speeds; filters for incoming and outgoing air need to be regularly replaced by the house owner. The complex has a shared heat-pump system that is connected to a collector of tubes that exchange heat with the underground. The heat extracted from the soil pre-heats warm water used for floor heating and hot water. For hot water (used in the bathroom) it needs to be electrically after-heated in a boiler tank. The house's kitchen contains small electric close-in boilers, one for boiling water, one for normal hot water from the tap.



### ***Energy use in 2010, the reference year***

After a year of use and only minor adjustments (replacing broke lightbulbs with more energy-efficient ones, the energy use measured was:

- Electricity 5,622 kWh
- Heat 36 GJ heat (from the heat-pump system)
- Total 56 GJ or 15.6 MWh

The total energy use come down to 1.77 kW of permanent power (in this case fully electric). This is already 27% less than the Dutch average house. So although the consumption of electricity is higher than average, the use of heat from a heat pump is so much lower than the usual use of gas, that the house could be called energy-efficient already.

### ***Measures taken since 2010***

Since 2010, all lighting has been replaced by LED and energy-saving fluorescent lighting. Based on calculation of sufficient levels of fresh air for a family of four, standard ventilation rates were brought down from 50 to 20% of full power, which also reduced noise levels indoors. The boiler temperature was reduced from 65 to 55°C, a level that safe enough against Legionella bacteria with short piping circuits. In August 2011, 5 m<sup>2</sup> of mono-crystalline PV was installed on the small flat roof of the house (15%, 550 W<sub>peak</sub> ~ 600 kWh/a). As a measure of effective flexible thermal insulation during winter evenings and nights, in November 2011 thick curtains were hung behind the large windows of the second floor. As a technical measure to fix the floor heating system, a much more energy-efficient water pump (from hundreds of Watts to 10 W on average) was installed in early 2013. Finally, and not unimportantly, the residents switched off boilers and electrical equipment when they were away for at least two days.

### ***Energy use since 2010***

Table 2 gives values for energy use figures, measured between 2010 and 2016. All values have been converted to 365 days, and heat values were calibrated according to degree days.

Table 2. Energy sources and energy content per unit

Date	Electricity	Savings	Heat	Savings	Total	Permanent	Savings
02-10-2011	4,676 kWh	17%	36.0 GJ		56 GJ / 15.6 MWh	1.77 kW	
31-10-2012	4,338 kWh	23%	25.6 GJ	29%	42 GJ / 11.8 MWh	1.35 kW	24%
16-11-2013	3,946 kWh	30%	74.7 GJ*	-108%	89 GJ / 24.7 MWh	1.82 kW	-56%
08-11-2014	3,822 kWh	32%	28.9 GJ	20%	43 GJ / 11.9 MWh	1.36 kW	24%
07-11-2015	3,739 kWh	33%	24.3 GJ	21%	38 GJ / 10.5 MWh	1.20 kW	26%

\* In 2013 a very odd measurement was done by an official of the energy company. Although no fraud by the official could be proven, the energy company returned the extra costs of 2013 in the years after, when the dwellers had proved the falseness. So this measurement can be ignored.

Converting the results of Table 2 to the main author only, taking the two kids as one adult, the personal use after these years of savings turns out to be 12.6 GJ or 3.5 MWh, 400 W permanent. This is 55% less than the average Dutch person. For this use of electric energy renewable power is purchased off an organic farmer with PV on his stables, via energy company Vandebron (literally ‘from the source’). So the house considered is not energy-neutral – it does not produce all of its own energy – but it is carbon neutral – all energy it uses is from renewable sources.

### ***Further savings***

Following the New Stepped Strategy [Dobbelsteen 2008], further reuse of waste heat (step 2) is difficult since heat from exhaust air is already recovered and installing heat recovery systems on waste water from the shower and bath is practically impossible.

That leaves the following measures for reducing the energy demand (step 1) still to be taken: achieving better airtightness by foam strips (executed in the winter of 2016), applying curtains in all rooms (still to be done), and using external sun-shading (see next).

A greater production of renewables (step 3) could be achieved by a solar collector, but in combination with the heat pump system already installed, the added value is very limited, and extra expenses disproportional. Adding more PV is only possible on the facades, for which approval is necessary of the house owners' society and municipal architectural committee. More interesting would be to combine external sun-shading with PV strips (louvres) on the south façade next to the roof terrace (a big source of undesired heat in summer). This is currently explored. Adding a small wind turbine next to the PV on the upper roof (for instance the Windleaf, by Windchallenge) is spatially possible but with a projected annual yield of around 800 kWh and an investment of more than 3000 euro, return on investment still takes about 20 years. It is however considered seriously.

It appears, as with many dwellings in dense inner-city locations, possibilities for personal production of renewable energy (and hence, becoming net-zero energy) is limited, leaving the sustainable procurement as a good option.

### **Personal transportation and commuter travel**

#### ***Situation before and after 1 January 2010***

In December 2009 the main author, following his appointment as full professor at TU Delft, moved from Amsterdam to Delft, changing his modal split from riding the train and cycling to and from stations to cycling directly to his faculty building. Regardless of this commuter transport there of course also is personal transport, which will be elaborated shortly here.

#### ***Cycling and walking***

Cycling costs approximately 60 kJ/km (per person). Energy for this comes from food. Before 2010, the main author cycled 5 days a week, 10 km a day, which comes down to 2,300 km a year. In energy this equals 138 MJ. After 2010 the cycling distance halved to a maximum of 5 km a day, 5 days a week, entailing an energy use of 79 MJ.

#### ***Public transport: train rides***

Trains use 80 Wh/p.km of electricity, based on average occupancies in Dutch trains. Before 2010 for his commuter transport the main author travelled 5 days a week over a distance of 72 km, a total annual distance of 33,000 km. The electric energy needed for this was 2600 kWh (9.36 GJ). After 2010 this dropped to an average of train business trips of 80 km a week, a total annual distance of 3,700 km. This implies an energy use of 294 kWh (1.06 GJ), 90% saved.

#### ***Private car use***

The main author has a private car, a Volkswagen Transporter T4 camper van with Transfalia infill. It has a 2.4-litre diesel engine, and it uses one litre for 11 kilometres on average. Hardly energy-efficient but seldomly used and a sustainable means of combining travelling with holidays on campsites in summer. The car is used for the whole family, two adults and two teens, which we count as 3 persons, so the individual share for the main author is one third.

Before 2010 the main author used the car for 12,000 km a year, using 1,090 l of diesel, which equals 36,3 GJ. Divided by three this means a personal use of 12.1 GJ. After 2010 care use dropped to 9,000 km a year, implying a use of 750 l of diesel with the energetic equivalent of 27,3 GJ. The main author's personal use therefore is 9.1 GJ.

### **Conclusion**

Seeing the figures for transportation one noticed the big difference of energy used for cycling, riding trains and driving cars. The car, even with a smaller distance covered than the train uses by far the most energy per person. For the main author's private travel the total energy use went from 21.6 GJ in 2010, to 10.2 GJ (2.8 MWh) after that year, an energy saving of 53%.

Since 2017 the Dutch railways ride on 100% of renewable energy (wind power) after one year of 50% of renewables. So the only real problem to become carbon neutral is the main-author's diesel-fuelled car, with a share of 41% of his total energy use, including the house.

### **Other factors of individual energy**

#### ***Business travel and the energy of flying***

Based on energy data of air travel the main author has kept track of his business trips since 2011, consisting of train rides in the Netherlands and neighbouring countries (Belgium, Germany, UK), some distances covered by car and flights. The energy use of airplanes strongly relies on the distance covered, the airplane itself and the occupancy.

Based on the distance and mode of transport, 2011 showed a relatively modest energy use of 3.2 MWh (11.5 GJ), 90% of the personal use of energy for the house. 2012 saw 3 intercontinental flights and 3 continental flights, which led to a total energy use of 47.6 MWh (171 GJ), seven times more than the energy used for house and personal travel. In 2013 business travel reduced to 42.7 MWh (154 GJ), in 2014 to 32.6 MWh (115 GJ), but thanks to the success of European research projects and international collaboration the energy consumed for business trips in 2015 and 2016 was greater than 50 MWh.

#### ***The energy of food***

As already introduced, food is an important factor for energy consumption. The term of 'food miles' indicates the distance that food has to travel to arrive in the supermarket; also the means of transport and necessity of frozen or chilled storage plays an important factor. Not to forget the production of food in greenhouses, under optimised conditions, requiring heating in winter, to mention one aspect. Meat and fish cost more energy than other foods; meat is the killer when considering greenhouse gas emissions [[www.landshare.org](http://www.landshare.org)]. So becoming energy-efficient and low-carbon requires a conscious lifestyle that includes wise selection of food. The authors made a calculation of average eating patterns and compared these to vegetarians or vegans, which made a big difference when taking an American lifestyle as the basis [US Department of Agriculture] and less so when looking at a continental European [RIVM]. In general, eating seasonally fitting food avoids a lot of energy for transport and storage. Most effective is eating less meat.

#### ***Other sources of individual energy use, not assessed***

There are many more elements of life that cost energy and that have not been assessed for this paper. For instance, pumping out rainwater, producing drinking water and processing wastewater all cost energy. Furthermore, the extraction, transport and processing of resources requires energy that can be considered as 'embodied energy' of materials and

products. A particular kind of products are clothes and what we may call stuff. Almost impossible to assess all of these, they form a part of everyone's life and choices, hence have an important influence on the environment.

## Conclusion

In total, in the year 2015, the individual considered used 22,8 GJ or 6,3 MWh for his house and personal travel. This is 41% less than the reference year and 49% less than the average Dutchman. The actions taken by the main author clearly led to a lower footprint. Of the energy used, 60% is carbon-neutral, the diesel van being the main problem to be solved. Net-zero energy living is possible but difficult when considering dense urban circumstances, but everyone can be carbon neutral when energy is procured from renewable sources. For mobility, unless one can fully use human-powered or public transport, becoming energy- and carbon-neutral is more of a challenge, and this particularly holds true for flying. The calculation of energy for flying goes to show that painstaking efforts to reduce the energy used at home to carbon-neutral and nearly zero-energy are terrifically over-compensated when flying for business (or for private goals).

If all energy used at work were to be accounted to employees, we would have to include many more sources of energy use: the office, ancillary company utilities, the conference for which this paper was written... Perhaps all of these factors should be included. After all, in the near future we will all have a carbon budget that cannot be exceeded, produced at home or at work does not matter then. Therefore, one of the next steps is to convert all energy use related to the university to all of its employees and students. Including these factors will increase the individual influence one can have on the national energy use from 30 to at least 50%.

This individual research clarified the greatest challenges and most effective strategies of living in a modern, dense city, with abundant access to unsustainable food and with easy opportunities to travel unsustainably for little money. As it held a mirror before the author, it will hopefully do as well before a greater audience.

## References

- Dobbelsteen A. van den; 'Towards closed cycles - New strategy steps inspired by the Cradle to Cradle approach', in: Proceedings PLEA 2008; UCD, Dublin, 2008
- Gore A.; *An Inconvenient Truth - The Planetary Emergency of Global Warming and What We Can Do About It*; Rodale, New York, USA, 2006
- Hermans J.; *Energy Survival Guide*; Leiden University Press, 2011
- IPCC (Intergovernmental Panel on Climate Change); *Climate Change 2014: Impacts, Adaptation, and Vulnerability*; IPCC, Switzerland, 2014
- PBL (Planbureau voor de Leefomgeving); 'Aanbod en verbruik van energiedragers in Nederland, 2015', URL: <http://www.clo.nl/indicatoren/nl0053-energiebalans-nederland-tabel>; Compendium voor de Leefomgeving, 2017
- Roggema R., Dobbelsteen A. van den, Stremke S. & Mallon W.; 'Spatial Energy Framework Aiming at Breakthroughs Brings Goals beyond Policy Objectives within Reach', in: Jenkins A.L. (ed.), *Climate Change Adaptation* (127-150); Nova Science Publishers, 2011



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Users in context: actions and practices in low energy buildings

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**Abstract:** One of the key challenges of the building industry is to achieve the expected performance in buildings in-use. The literature shows significant gaps between the as-designed and in-use building performance. There is a pervasive assumption among design practitioners and facilities managers that the occupants and their actions in buildings are a primary source of these 'performance gaps'. This paper contests two misleading notions that underlie that assumption: 1) the view that the user is a 'passive agent' in the built environment; and, 2) the view that there is a 'typical' user that can be applied universally. This paper presents a study that investigated the occupants' actions in four BREEAM certified buildings, comparing their as-designed and in-use performance. The study applied post occupancy evaluation techniques and user studies to investigate occupants' practices to provide explanatory detail to monitored environmental and energy consumption data. The paper focuses on occupants' actions and facilities management practices enacted in the everyday operation of buildings: what users do to achieve comfort, which include reconfiguration within spaces, adaptation through clothing, and operating building technologies; and, the facilities management strategies to operate the building. All of these take place against a background of institutional policies and norms. The observed actions and reported practices bring challenges to the typical representation of users and facilities management practices embedded in as-designed models of building performance. Therefore, an in-depth understanding of the context of building use considering different stakeholders' perspectives is deemed valuable to inform effective design strategies for building performance as well as to develop interventions to reduce the energy consumption of existing buildings.

**Keywords:** in-use building performance, building user, energy consumption, comfort, post occupancy evaluation

### Introduction

The building industry is facing increasing demands to create energy efficiency buildings and reduce the carbon emissions of the building sector. The non-domestic building sector accounts for 20 per cent of carbon emissions in the UK. Therefore, attention is centred to improve the performance of existing non-domestic buildings. A review of the energy performance gap in the non-domestic sector suggests that 10-80% of the performance gap found in operation could be attributable to occupants' actions (van Dronkelaar et al., 2016). Typically, approaches to reduce energy consumption during operation have emphasised control strategies that restrict the actions of the users as a means to prevent their inconvenient and inefficient energy behaviour. However, building performance is the result of design features and their effectiveness to meet the expectations of occupants (Cole et al., 2010). Occupants' actions and any resulting performance gap could originate in how the occupants' expectations are met (or not) in the everyday use of buildings. There is a need to understand the actions and behaviours of everyday use and operation of buildings as a way to inform strategies for the efficient operation and management of existing buildings and

for the building industry to learn from real buildings in operation and improve future building design (Janda, 2011, Fedoruk et al., 2015). The literature highlights that building occupants do not operate in a vacuum. The occupants have and exert agency to achieve desired conditions and to develop the actions in the daily occupation of buildings. In the context of non-domestic buildings, the individual and group agency of occupants could also be shaped by the social and cultural context (Lorch, 2008, Inalhan et al., 2010). Human agency manifests in the social context of use (Krippendorff, 2006). Krippendorff argues that the user should be regarded as 'knowledgeable agent whose actions are not arbitrary' (Krippendorff, 2006). Building upon the literature, this paper presents a research that investigated the users' actions and management practices relevant for thermal comfort in the light of the organisational culture and policies of four BREEAM certified buildings.

## Methodology

The study applied post occupancy evaluation techniques and user surveys to identify occupants' satisfaction with and actions to modify indoor environmental conditions (thermal, lighting, acoustics) in four case studies. The purpose of the study was to identify how the social and organisational aspects encouraged (or discouraged) the occupants to modify the indoor environmental conditions and informed the management and the operation of the buildings. This paper focuses on the findings related to thermal aspects, referring, as relevant, to other indoor environmental conditions to highlight the nexus between thermal, lighting and acoustic conditions in providing the conditions for the satisfactory use of buildings as perceived by the research participants. The case studies were four BREEAM Excellent buildings: two schools and two offices buildings, certified to BREEAM 2006 version. Table 1 summarises the key performance aspects of the case studies.

Table 1. Summary of the case studies

Case Study	1	2	3	4
Building type	Office	Office	School	School
Location	South Wales	SW England	SE England	South Wales
BREEAM Rating	Exc.(73.89%)	Exc.(74.42%)	Exc.(71.97%)	Exc. (73.42%)
BREEAM version	Offices 2006	Offices 2006	Schools 2006	Schools 2006
Area m <sup>2</sup>	3736	1130	10996	2116
BER KgCO <sub>2</sub> /m <sup>2</sup>	24.88	14.81	11.40	8.50
%better2006 regs	40.85	12.90	33.91	37.9 0
BREEAM Energy	14 credits	10 credits	14 credits	15 credits
EPC desg.[in-use]	A [B(31)]	A	A [B(27)]	A [C(72)]
*Features for energy efficiency	NVB, Wind-man, Wat-boi	LZC, UFH, NVB, Rad, Wind-CO <sub>2</sub> , Wind-Man, Wat-solar	>15% by LZC, UFH, NVB, Wind-CO <sub>2</sub> , Wind-Man, Wat-solar	15% by LZC, UFH, NVB, Wind-CO <sub>2</sub> , Wind-Man, Wat-solar

\*Abbreviations: (LZC) Energy supplied by low zero carbon technology; (UFH) Underfloor heating, (Rad) radiators, (NVB) naturally ventilated building, (Wind-CO<sub>2</sub>) operation of windows by CO<sub>2</sub> levels, (Wind-man) manually operated windows, (Wat-solar) solar thermal for water heating, (Wat-boi) Boiler for water heating

The indoor environmental conditions (temperature, CO<sub>2</sub> levels and relative humidity) and the electricity and gas consumption were monitored for a year. The user studies were carried out across four visits (one per season) and comprised semi-structured interviews, questionnaires and walkthroughs. The studies collected qualitative data about actions and perceived satisfaction with energy and indoor environmental conditions (thermal, lighting and acoustics). They included an additional spot monitoring exercise that recorded the indoor environment parameters (internal air temperature, mean radiant –globe-temperature, relative humidity, illuminance levels and ambient noise level) to link users' satisfaction and actions to the monitored conditions on the day of the visit.

### ***User studies—Instruments***

During the user studies (one visit per season), the environmental conditions were monitored at 10-minute intervals, recording the internal air temperature (°C), mean radiant (globe) temperature (°C), relative humidity (%), illuminance levels (lux) and ambient noise levels (dBEqA). A morning and an afternoon reading of external air temperature were recorded on the day of the visit. The equipment used for monitoring the conditions during the visits were: (1) Testo 435 anemometer to record the air speed and the temperature; (2) Digital impulse sound level meter Dave D14-22C and calibrator Serial # 3742070; and, (3) Eltek squirrer data logger 1000 server to record the globe temperature, lux and relative humidity.

### ***User studies—qualitative study***

The user studies investigated the occupants' actions and management practices in the buildings. Questionnaires were administered to students and employees in the case studies. The questionnaires included questions about the perceptions, satisfaction levels, knowledge of systems and controls, actions taken to achieve comfort. Three questionnaires were administered per seasonal visit: one general questionnaire and perceptions/actions in the day repeated in the morning and in the afternoon of the seasonal visit. The general questionnaire included questions about the building in general. The repeated questionnaires focused on reporting about the space where the respondent is based. The repeated questionnaires data were analysed in the light of the indoor environmental data monitored on the day. In addition to the questionnaires, semi-structured interviews with open-ended questions were conducted to facilities managers and different user representatives (teacher, employees in the office, head teacher and office manager). The mix of participants enabled to depict multiple perspectives with regards to how the buildings were used: the end-user engagement in everyday use of building (ie. data from employees), the medium-long term management of facilities (ie. data from facilities manager), the corporate norms and impact on the building management activities (ie. data from the head teacher, office manager). The length of the each interview was between 45 and 60 minutes. Documents such as the Operation and maintenance manual and the BREEAM reports were analysed to identify the as-designed energy and environmental performance intentions.

## **Findings**

The users in all of the case studies expressed their willingness to take action to modify their immediate indoor environment to achieve comfort when the indoor conditions were not

satisfactory. The main reason for dissatisfaction in the buildings was overheating, which was reported at different times of the year as shown in Table 2.

Table 2 Temperature recorded during seasonal visit (Tmp °C) and percentage of occupant's complaints due to overheating (Ovht %)

Seasons	CS 1	CS 1	CS 2	CS2	CS3	CS3	CS4	CS4
	Tmp °C	Ovht %	Tmp °C	Ovht %	Tmp °C	Ovht %	Tmp °C	Ovht %
Summer	24-25.6	71.43	23.2- 24.4	85.71	24.5-28	66.70	27-31.8	100.0
Autumn	21.6- 22.6	37.50	23.7- 24.1	28.57	21.6- 22.6	100.0	21.7- 23.75	60.0
Winter	23-24.5	28.57	22-24		22.6- 23.3	66.70	20-21	
Spring	24-25.4	14.29	22-24.5	14.29	24.8- 25.5	60.00	19.8- 21.5	77.78

The types of action taken by the research participants to improve their thermal comfort were: reconfiguration of spaces to match the location of workstations to individual thermal preferences (those who tend to feel hot next to windows, those who tend to be cold next to radiators); personal adaptation (i.e. adding/removing layers of clothes and taking hot/cold drinks); operation of windows and doors; use of fans and fan heaters.

Occupants in Case Study 1 (office building) were encouraged by the management team to exert adaptation strategies to achieve comfort: flexible dress code, relocation of workstations in the office and the use of personal fans and lamps in the workstations. The location of the workstations for individual employees is based on their thermal preferences. Employees working on the second floor, an open plan office area, chose the location of their desks (next to a window, in the core of the space, on the perimeter of the office by a radiator):

*Interviewee CS1: 'We have had people who specifically asked to move desks to somewhere else because they were hot or cold. One of our girls used to sit near the window but she is really cold so when other of the staff wanted the window opened, she was not happy. But of course, the ones in the middle wanted to get a bit of flow of air so she moved away from the window and near the radiator so in the winter she would have the radiator. So people have said I don't like it here, it's too hot, too cold and moved appropriately to a better position.... still you can't please everybody but we've tried the best we can to sit people in a position that make them in a more comfortable environment.'*

A personal fan and fan heater are used in 75% of the individual workstations. The support provided at corporate level to the employees in Case Study 1 to be comfortable is motivated by the desire of the company to enhance the employee's productivity by increased comfort.

The research participants in all the case studies expressed their willingness to modify the thermal conditions of the spaces that they occupy. This was manifested by adaptation actions exerted at personal level and at building/technology level. The typical actions at building/technology level included the operation of windows and doors and the use of fans. However, some building features and control strategies in the case studies did not support adaptation despite the design intentions. For example in Case Study 4, the teachers expressed their desire to use windows and doors to improve the ventilation in the

classrooms for thermal comfort and for fresh air. However, these actions were restricted by the layout of the school. The manually operable classroom windows in the first floor open to a buffer ventilation area. The ventilation area was originally designed for minimum occupancy, as a play area when the weather conditions did not allow the use of outdoor play area. The buffer area is a double-height space connected to the nursery area on the ground floor and adjacent to classrooms with manually operable windows on the first floor. The buffer area has been converted to a permanent play area for nursery children on the ground floor due to lack of spaces, restricting the use of the operable windows of the classroom in the first floor. When the windows in the classrooms are open, the noise from the nursery disturbs the classroom activities (78dBC). While the doors of the classrooms could be open for ventilation, the teachers prefer to keep the doors closed to avoid noise from the corridor (113.4dBC). When the building overheats, the teachers tend to switch off the lights in the classrooms to limit the lighting heat gain. This action in turn compromises the lighting levels in the classrooms (267-305lux). These classrooms also have windows at ceiling height that are automatically controlled on the basis of CO<sub>2</sub> levels. These windows open to the exterior but cannot be manually operated because they are out of reach (approximately 2.60m high). The caretaker in Case Study 4 reported that the CO<sub>2</sub> levels that trigger the operation of the windows are changed seasonally so that the automatic windows open more frequently in summer (to reduce overheating) than in winter (to prevent incoming cold air). The CO<sub>2</sub> levels that trigger the opening of windows in winter is 1250-1750ppm. In summer season, the CO<sub>2</sub> level trigger point is 750-1550ppm. This strategy, however, is problematic when the CO<sub>2</sub> levels rise and there is rain, cold air or drafts due to outdoor weather conditions and during autumn and spring. It should be noted that CO<sub>2</sub> levels can build up to unadvisable levels in winter; yet, the windows remain closed. Another criticism of the automatic windows was the noise and disruption created when they open during teaching activities that required concentration. In Case Study 4, the occupants wanted to modify the immediate environment (which in turn could increase their perceived satisfaction in the building); however, there were limited opportunities for the occupants to use effectively the building features (windows, doors) to support adaptation.

A similar situation was reported in Case Study 3. The research participants expressed their desire to exert a range of adaptation actions: personal (clothing according to the season) and to operate the building technologies in the spaces that they occupy (windows, doors, blinds). However, at organisational level, some school policies limited the adaptive opportunities available to occupants. In terms of personal actions, the dress code for employees strongly recommends suits and ties to be worn all year round to present a professional image to the students and parents. Occupants were not allowed to wear lighter clothing in summer. For the operation of building technologies, there was a policy to not operate windows or blinds in the spaces adjacent to the main façade. The intention was to maintain the uniformity of the main façade to avoid that this facade '*looks as if it is missing some teeth*' when some windows/blinds were open while others remained closed. The use of windows in upper level floors was also restricted due to safety concerns.

The facilities manager in Case Study 3 reinforced this view by expressing his discontent with the corporate expectations about his role. He felt that there was little support for him to promote activities to reduce the energy consumption. He thought that he was expected to focus on the provision of the physical conditions of classrooms (sufficient space, number of computers, chairs and resources for teaching) rather than the management of indoor environmental conditions and energy performance. He felt that the actions to manage the

indoor environmental conditions were supported at corporate level if triggered by unexpected problems in the classrooms rather than as a planned programme of management and maintenance. It should be noted that this was the only case study with onsite availability to BMS data. However, there were problems with the metering and possible data corruption. Yet, there had been no support to fix the BMS problem which prevented the facilities manager from having robust recorded energy and environmental data that could inform medium and long-term plans for performance management.

The data indicate that the organisational policies shape the management practices and actions available to the occupants to achieve thermal comfort in the case studies. For example, in Case Study 2, the facilities management role was fulfilled by a team offsite. Case Study 2 is a building that belongs to an institution with its main headquarters in a different location. The Estates department deals with the energy management of the building, including the automated building controls and the access to the monitored data by the BMS. There is limited control directly available to the building occupants in Case Study 2 to modify their indoor environment. The windows operate automatically on the basis of CO<sub>2</sub> (like Case Study 4) although the occupants can override the system and operate the windows manually. There is no dedicated facilities manager in this building. When a problem arises in Case Study 2, a technician whose role includes 'facilities management tasks' contacts the Estates department. The Estates department is perceived to be helpful although they are unable to respond immediately to the problems in Case Study 2. One source of dissatisfaction is the automatic operation of windows. Windows open in weather adverse conditions (rain/draft/cold) and interfere with activities in the office. The technician felt that the building management activities should take place onsite for a more efficient operation of the building. Table 3 summarises the key findings concerning facilities management aspects and institutional policies and norms that enabled (or discouraged) the adaptation actions.

Table 3 Summary of facilities management aspects and corporate support to initiatives

Case Study	1	2	3	4
BMS	No BMS	BMS off-site, by internal organisation	BMS onsite, problems-data corruption	BMS off-site, by external organisation
FM's role	No FM/office manager	FM Off-site, technician onsite troubleshooting	FM on site, troubleshooting	No caretaker, FM/troubleshooting
*Corp. comfort	Yes, productivity	Neutral	No: reputation, aesthetics, safety	Neutral
**Corporate pro-EneEffic.	No	Reduction of electricity use	No	Reduction of electricity use

\*Corporate norms/policies that supported initiatives to achieve comfort; \*\*Corporate norms/policies that supported initiatives to reduce energy consumption

## Discussion and conclusions

The research data suggest that occupants are willing to modify their thermal conditions through personal adaptation and by using building technologies/features (windows/doors). This is manifest in the following strategies: (1) rearrangement of the space (dynamic use and location of workstations in relation to individual thermal preferences in Case Study 1); and, (2) Adaptation actions observed in all of the case studies, in alignment to the thermal

comfort theory (Brager and De Dear, 1998). However, the data also suggest that corporate policies could support (and discourage) the adaptive opportunities available to occupants. In Case Study 1, the company supported actions to achieve comfort to enhance employees' productivity. In Case Study 3, corporate norms limited adaptation: restricted dress code, restricted operation of windows/blinds. In Case Study 4, the opportunities to operate the windows were restricted by the change of use in a space originally designed as a ventilation area. The organisational context, therefore, could potentially have an effect on the scope of individual and adaptation actions available to building occupants. In other words, the actions for comfort and the operational practices at facilities management level (and alike-i.e. caretaker) took place against a background of institutional policies and norms. The range of the actions available to different stakeholders (occupants, facilities managers) seemed to vary in relation to the institutional context. It should be noted that the management and the operation practices were not driven by energy and environmental targets in the case studies. Case Study 3 had a facilities manager onsite who did not exert direct actions for energy and environmental management. In one case study, the facilities manager was located offsite and in two case studies there were no facilities managers in house. There was a general opinion that facilities management was a reactive rather than the proactive role needed to enhance the energy and indoor environmental performance or to foster the efficient operation of the buildings.

This work has provided insights into occupants' actions and facilities management practices in relation to institutional norms and policies. The results draw attention to the complex context of building use and operation and question the simplistic notions that regard the user as a passive agent and the stereotypical user as a standard 'concept'. Ultimately, the paper advocates a more sophisticated understanding and more nuanced representations of users, in contradiction to the typical 'one size fits all approach' to inform energy efficiency interventions and strategies to improve the operational performance of existing buildings. Such a need is already recognised by service design approaches for the design of many new buildings, when the concept of 'personas' prevalent in user-centred product and technological system design is used to explore possible interactions between different types of users and the managed buildings they will inhabit. The acknowledgement of the agency, the knowledge and the non-arbitrary actions of building occupants within the context of organisational norms and policies are key propositions to analyse the 'counterintuitive' and 'inefficient' occupant behaviour. That stance puts inhabitants at the centre of the debate to achieve energy and environmental performance targets in existing buildings. Their different perspectives could inform interventions guided by the concerns and needs that are relevant to the users with a view to enhance the energy and environmental performance of existing buildings.

Further research will examine how corporate goals and individual goals could be linked to energy efficient intentions. For example, it is widely recognised that good indoor environments have positive effects on occupants' health and wellbeing: increased productivity, reduced absenteeism, better educational attainment. These aspects are likely to be relevant to occupants' concerns and corporate goals and could be nudging points to motivate the proactive and efficient management of building performance. The energy efficiency initiatives in non-domestic buildings seem to sit within three layers of action: building occupants, facilities management and the organisation/corporate level. Aligning the different visions of these stakeholders may result in more effective ways of operating

buildings. This could provide feedback to designers to enhance their understanding of operational performance and to inform the design representations of occupants.

### **Limitations**

The user studies aimed to explore the indoor environment variations experienced in the buildings throughout the year and within the day of the visit (morning and afternoon) by investigating the participants' responses in relation to the specific indoor environment conditions of the day of the visit. They are not representative of the season. The user studies investigated the occupants' actions and facilities management practices that take place within the organisational policies; aspects that are relevant to the achievement of energy and environmental performance targets in existing non-domestic buildings.

### **References**

- BRAGER, G. S. & DE DEAR, R. J. 1998. Thermal adaptation in the built environment: a literature review. *Energy and buildings*, 27, 83-96.
- COLE, R. J., BROWN, Z. & MCKAY, S. 2010. Building human agency: a timely manifesto. *Building Research & Information*, 38, 339-350.
- FEDORUK, L. E., COLE, R. J., ROBINSON, J. B. & CAYUELA, A. 2015. Learning from failure: understanding the anticipated–achieved building energy performance gap. *Building Research & Information*, 43, 750-763.
- INALHAN, G., BROWN, Z., COLE, R. J., ROBINSON, J. & DOWLATABADI, H. 2010. Evaluating user experience in green buildings in relation to workplace culture and context. *Facilities*, 28, 225-238.
- JANDA, K. B. 2011. Buildings don't use energy: people do. *Architectural Science Review*, 54, 15-22.
- KRIPPENDORFF, K. 2006. The semantic turn: a new foundation for design. *ARTIFACT-ROUTLEDGE-*, 1, 51.
- LORCH, R. 2008. *Buildings, culture and environment: informing local and global practices*, John Wiley & Sons.
- VAN DRONKELAAR, C., DOWSON, M., SPATARU, C. & MUMOVIC, D. 2016. A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering*, 1, 17.

# Building Performance Evaluation

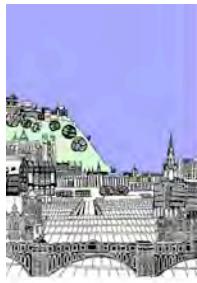
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*Design to Thrive*

## A study on the evaluation of thermal comfort of occupants, summertime and wintertime temperatures in a single prefabricated structural timber dwelling

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**Abstract:** This study evaluates occupants' comfort, summertime and wintertime temperatures in a timber dwelling unit located in Milton Keynes, UK. The study was conducted in July, 2012 for the summer survey and from January-February 2013 for the winter survey. The study employed a combination of thermal comfort survey and on-site measurement of parameters (temperature and relative humidity). The findings revealed the occupants feel warm in summer but thermally satisfied in summer and winter. The monitoring results using the static and adaptive comfort models showed summertime overheating occurs in the living room (7.0% each time above the 28°C and the BSEN15251 Category II upper indicators) and the bedroom (18% and 15% each time above the 26°C and the BSEN15251 Category II upper limit respectively). Higher neutral temperatures (summer – 1.8°C; winter – 0.8°C), preferred temperatures (summer – 1.1°C; winter – 2.6°C), and mean temperatures (summer – 0.5°C; winter – 1.3°C) are reported in the bedroom than the living area. The results showed the ability of occupants to have higher adaptation to the thermal environment in bedrooms than living rooms. Finally, the results revealed the ability of timber dwellings to provide more comfortable indoor conditions to occupants in winter than summer.

**Keywords:** Thermal comfort, summertime and wintertime temperatures, thermal comfort survey and on-site measurement, thermal comfort models, prefabricated structural timber dwelling.

### Introduction

There are various studies that have investigated thermal comfort of occupants in residential buildings [1-6]; a few studies on thermal comfort of occupants have addressed occupants' comfort in dwellings [4-5]. Generally, the primary needs for people to survive in any climate include food, clothing, and dwelling. Of these three basic needs, people aspire and have preference for dwellings with favourable and comfortable conditions in summer and winter due to harsh external weather conditions aggravated by climate change. Most people want to acquire and live in dwellings with acceptable comfort condition but acquiring dwellings tend to be the most critical and in many instances the highest expenditure item in people's lifetime. These further contribute to why most people have preference for dwellings that provide the most comfortable conditions [7]. In recent decades, more sustainable dwellings are constructed with materials that have low-carbon footprints. Investigations on thermal comfort of occupants in energy-efficient dwellings and the ones built with green materials such as bamboo, structural timber are important to understand occupants' adaptation and behavioural actions [4] as well as to reduce overall energy used in dwellings. As mentioned

in existing studies, energy used in dwellings accounts for about 29% of the total energy consumed in the UK in 2015 [8]; while it accounts for almost 40% of the total energy consumed in the US in the same year [9].

As reported in previous research, thermal comfort of occupants is one of the most crucial parameters evaluated in order to understand the thermal environment of various dwellings [7]. A recent study stated that investigations on thermal comfort of occupants can provide a better understanding of a range of temperatures at which occupants prefer no change as well as feel neither warm nor cold in summer and winter [4]. Existing studies have evaluated occupants' comfort in UK dwellings [1-6]. These studies considered short-term [1,5] and long-term assessments of occupants' comfort in summer [3-4,6]. A few studies addressed occupants' comfort in wintertime [1,5]. On-site measurements of buildings built with heavyweight materials such as concrete, bricks are also investigated [2-3] while measurements of timber buildings in summertime are considered in some studies [1,4-6]. To date, only a few studies on occupants' comfort in UK timber dwellings have been conducted due to the limited number of timber dwellings in the nation [10] when compared to the number of timber dwellings in the United States and Scandinavia [11].

Existing studies have revealed that overheating occurs in UK dwellings, especially in dwellings located in the warmest regions [1-3]. The climate (UK's climate) is considered to be wet and mild in summer [5] and cold in winter [11]. Research has also been conducted to investigate overheating in dwellings located in UK cold regions [6]. A study conducted in 282 UK homes [3], and another investigation [2] revealed high temperatures are observed in UK dwellings in summer. However, these studies [2-3] only considered on-site measurements of dwellings with limited or no information on subject votes in summer. A recent study showed that overheating occurs in timber dwellings in Scotland [6]. The study was conducted on timber frame buildings since they are common in Scotland and stated various causes of overheating in timber dwellings [6]. Summertime overheating has been evaluated in previous studies using different comfort models [3-4]. The two most widely used thermal comfort models for evaluating risk of overheating include the CIBSE 'static' model [12-13], and the adaptive comfort model [14]. Existing studies have highlighted that UK dwellings are prone to summertime overheating with a different degree of overheating reported in different studies [4]. Subject votes were also collected and analysed in various dwellings [1,4-5]. Attention was however paid to thermal comfort of occupants and summertime temperatures [2-5] with limited or no information on wintertime temperatures.

Past studies have also considered post-occupancy evaluation (POE) to investigate occupants' comfort in summertime [4-5]. An existing study has presented its findings on occupants' comfort in spring, summer, autumn, and winter [1]. The study explored a combination of subject votes and on-site measurements as the research methodology. The study [1] considered comfort temperatures in summer and winter with limited information on neutral and preferred temperatures. The study however evaluated mean temperatures and presented the mean votes on thermal sensation and thermal satisfaction during the field study [1]. From the literature, it is clear that additional studies are required to understand occupants' comfort and the performance of timber dwellings in summer and winter [4]. Also, timber is increasingly used for construction of dwellings in recent years in many parts of the world due to its green credentials, aesthetic appearance, cost, workability, ease of transport, speed of erection, and ability to capture carbon as long as it exists [4,10].

Based on the gaps identified from literature, this study investigates thermal comfort of occupants, summertime and wintertime temperatures in a single prefabricated timber

dwelling. Existing studies have mentioned that dwellings built with structural insulated panels (SIPs) are likely to be prone to overheating than dwellings built with cross laminated timber (CLT) panels [4,11]. As a result, it is important to understand occupants' comfort in summer and winter in dwellings built with SIPs. Moreover, this study aims to understand mean, neutral, and preferred temperatures in the living area and bedroom of the case study dwelling. The study also intends to understand if the outcomes of the research align with findings from existing studies on bedrooms being warmer than living areas [4,15]. This study aims to contribute to recent and on-going studies on thermal comfort of occupants in timber dwellings. The paper provides a better understanding of occupants' comfort in structural timber dwellings.

## Methodology

The research study employed a combination of thermal comfort survey using subjective questionnaire and on-site measurements. The parameters (temperature and relative humidity) were measured every hour. The study was conducted from Jul 24-31, 2012 for the summer survey and from Jan. 28-Feb. 8, 2013 for the winter survey. The HOBO and TinyTag data loggers were used for the on-site measurements. The parameters were measured at 1.1m above the floor level as specified by the ASHRAE [16]. The questionnaire was completed three times a day. The outdoor weather data for the same periods (summer and winter) were collected from Luton Airport weather station. The subject votes using 7-point scale (from cold to hot) for thermal sensation and 5-point scale for thermal preference (from much cooler to much warmer) were considered (Fig. 1) and analysed while the measured indoor and outdoor weather data were plotted in charts.

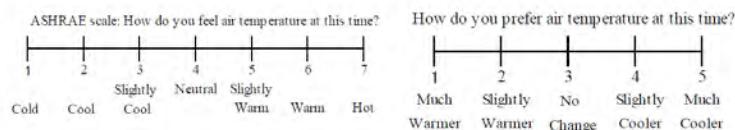


Figure 1: Examples of 7-point ASHRAE thermal sensation (left) and 5-point thermal preference scales (right)

The questionnaire was developed in a simple format for participants to easily understand and tested before it was distributed. Subject votes were analysed using the appropriate statistical software (SPSS and Excel) to find mean values, plot histograms and different charts including regression, as well as establish correlations between various parameters examined. Thermal comfort models (the CIBSE and the adaptive models) were employed to understand summertime temperatures since the dwelling is considered to be naturally ventilated in summertime. The CIBSE model was considered for evaluation of comfort temperature in wintertime and the adaptive model was not considered due to heating required in the season. For the CIBSE model, this study examined number and percentage of hours of temperature above the indicators (1% > 28°C for living area; 1% > 26°C for bedroom) [12-13]. Regarding the adaptive thermal comfort evaluation, the Category II '*acceptable conditions for newly built and refurbished dwelling*' was considered. The evaluation of comfort temperature focused on number/percentage of hours (5% of hours above the Category II upper thermal comfort envelope) to establish warm discomfort and (5% of hours below the Category II lower level) to identify cold discomfort [14].

## Case Study

The dwelling is an end-terraced unit and one of the completed 116 dwelling units located in Milton Keynes, UK. The housing development has won various awards due to the material

used for its construction and green credentials. The dwelling unit consists of living area, dining/kitchen on the ground floor while two bedrooms and study area are located on the upper floor (Fig. 2). The unit is occupied by a family of four (two adults and two young people). One of them works from home which revealed the dwelling is occupied nearly every time while the second adult works from home but not on a regular basis. The floor area of the unit is 76.8m<sup>2</sup>, and floor-to-ceiling height is 2.35m. The floor areas of the spaces monitored include living area (20.9m<sup>2</sup>) - southwest orientation and bedroom (12.2m<sup>2</sup>) - southeast orientation. The dwelling is constructed with building components that have low U-values: walls – 0.12W/m<sup>2</sup>K; roof - 0.17W/m<sup>2</sup>K; and windows - 1.7W/m<sup>2</sup>K.

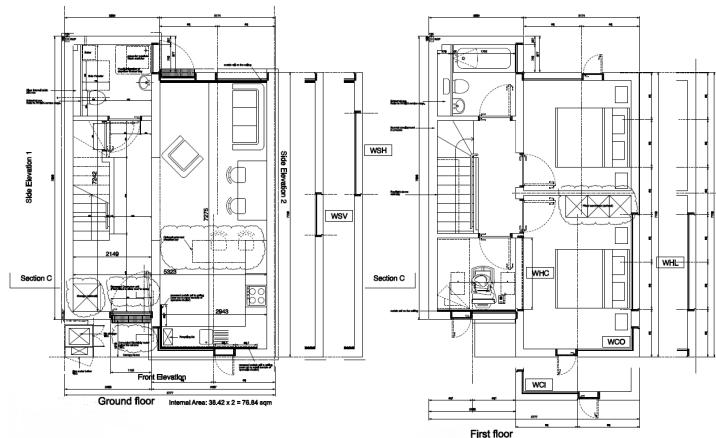


Figure 2: The ground floor plan (left) and the first floor plan (right) of the dwelling unit (RSHP Architects)

## Analysis

The analysis showed external temperature was between 8.0°C (minimum temperature) and 27.0°C (maximum temperature). The average external temperature was 16.6°C. The indoor temperature was from 19.8°C - 30.0°C in the living area and between 20.5°C and 28.8°C in the bedroom in summer. In winter, the external temperature was from -1.0°C to 13.0°C. The mean external temperature was 5.1°C. Table 1 below provides a summary of the measured temperatures in the living area and the bedroom in summer and winter. The analysis showed the external temperature was below 18.0°C for more than 50% of the time in summer. Likewise, temperature was within the comfort range (22.0°C – 25.0°C) in wintertime (Fig. 3). In addition, humidity was within 40%-60% in the summer; while it was within a wider range of 30%-80% in the winter. Table 2 provides summary of the subject votes in the living area and the bedroom.

Table 1. Summary of the measured internal and external temperatures including running mean temperature

Space	Summer Temp. [°C]			Winter Temp. [°C]		
	Mean Temp.	Max. Temp.	Min. Temp.	Mean Temp.	Max. Temp.	Min. Temp.
Living room	23.5	30.0	19.8	18.9	21.8	17.5
Bedroom	24.0	28.8	20.5	19.6	22.9	17.7
External temp.	16.6	8.0	27.0	5.1	13.0	-1.0
Running mean	17.8	18.9	15.9	NA	NA	NA

Table 2: Summary of the subject votes in the summer and winter

Space	Summer			Winter		
	Thermal sensation	Thermal preference	Thermal satisfaction	Thermal sensation	Thermal preference	Thermal satisfaction
Living room	5.2	2.6	6.1	3.8	3.0	5.8
Bedroom	5.4	2.9	6.3	4.0	3.4	6.2
Unit average	5.3	2.8	6.2	3.9	3.2	6.0

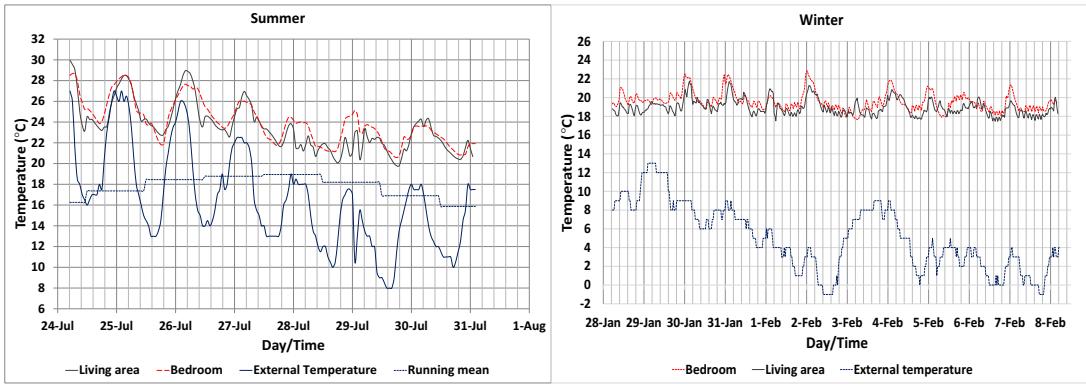


Figure 3: Measured temperatures in the living area and the bedroom

## Results and Discussions

The findings showed the monitoring period in summer was not an extreme summer period which could have contributed to high temperatures recorded in the living area and bedroom. However, the results revealed high temperatures were reported in the summer. The subject votes revealed the occupants feel warm in the summer and feel slightly cool in the winter (Table 2). The respondents prefer to be cooler than they were in the summer but prefer no change (that is, neutral) in the winter. However, the occupants are thermally satisfied with the thermal environment in both seasons. More than 80% of the votes revealed acceptability of the thermal environment in the summer and the winter. The result on thermal acceptability is in agreement with ASHRAE's recommendation [16] that at least 80% of the occupants must find the thermal environment acceptable.

Relationships exist between the internal and external temperatures in the living area and the bedroom. The bedroom is found to be warmer (about 1.0°C higher) than the living area in the summer and winter (Fig. 4). The floor layout of the dwelling unit may be a contributing factor to the bedroom being warmer than the living area due to the location of the bedrooms on the upper floor of the dwelling (Fig. 2). Since hot air rises, it is possible hot air moves from the lower floor to the upper floor where bedrooms are located. Temperature is also found to be within a higher range in the bedroom than the living area (Fig. 4). The result showed the possibility of higher temperatures to be frequent in the bedroom especially at night which may affect the quality of sleep during the period.

Using the CIBSE 'static' and adaptive comfort models to evaluate the risk of summertime temperatures in the living area and the bedrooms, the results showed summertime overheating occurs. The measured temperature rose above the 28°C indicator for over 12 hours (7%) during day-time (08:00am-10:00pm) out of 167 hours of monitoring and it rose above the BSEN15251 Cat. II upper indicator for more than 7% of the time in the living area. In the bedroom, the measured temperature rose above the 26°C indicator for over 18% of the time during the same period and it rose above the BSEN15251 Cat. II upper indicator for over 15% of the time (Fig. 5). The results showed the bedroom is prone to extreme summertime overheating and occupants are likely subject to warm discomfort in summer. In winter, the results showed the measured temperature did not rise above the 28°C indicator at any time in the living area and it was below the 26°C in the bedroom throughout the period of the survey.

Regarding the neutral temperature as well as the preferred temperature in the living area and the bedroom in the summer and winter, relationships exist between the variables especially in the summer (Fig. 6 and Fig. 7). The results showed higher neutral (at least 0.8°C, preferred (at least 1.1°C) and mean temperatures (at least 0.5°C) are recorded in the

bedroom than the living area in the summer and winter (Table 3). Preferred temperature is significantly higher by 2.6°C in the bedroom than the living area in the winter. This may be attributed to a change in use of space in summer and winter. Occupants that work from home preferred to work in the spaces on the upper floor of the dwelling unit in winter while the lower floor is preferred in the summer. The results showed higher adaptability of occupants to the thermal environment in the bedroom than living area. The mean, neutral and preferred temperatures in the summer and winter are presented in table 3 below.

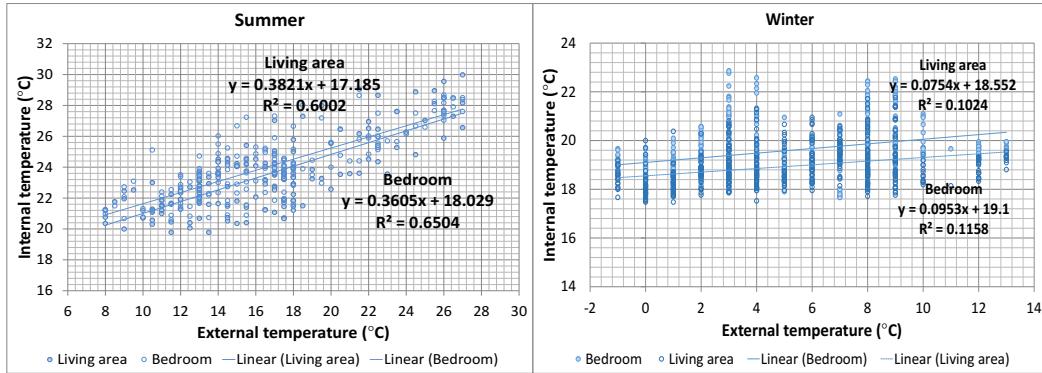


Figure 4: Relationship between measured temperatures in the living area and the bedroom

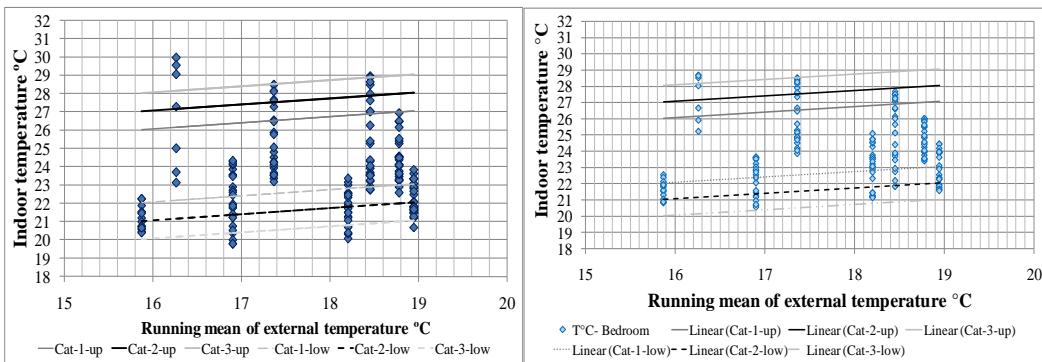


Figure 5: Temperatures in the living area (left) and bedroom (right) compared to the BSEN15251 levels.

Table 3. Summary of the neutral and the preferred temperatures in the summer and winter

Space	Summer Temp. [°C]			Winter Temp. [°C]		
	Neutral Temp.	Pref. Temp.	Mean. Temp.	Neutral Temp.	Pref. Temp.	Mean Temp.
Living room	22.1	22.2	23.5	17.6	20.8	18.9
Bedroom	23.9	23.3	24.0	18.4	23.4	19.6
Unit average	23.0	22.8	23.8	18.0	22.1	19.3

Comparing the results from this study with existing studies on summertime and wintertime temperatures, it is observed temperatures especially neutral and mean temperatures are slightly higher in this study than existing studies [1,17]. This study further validated findings of previous research [4] that prefabricated timber buildings are prone to high summertime temperatures while lower temperatures may also be observed in winter due to low thermal mass of structural timber materials. The table below provides summary of comparison of summertime and wintertime temperatures with existing research (Table 4).

Table 4. Summary of comparison of summertime and winter temperatures with existing research

Study	Summer Temperatures [°C]			Winter Temperatures [°C]		
	Neutral	Preferred	Mean	Neutral	Preferred	Mean
This study	23.0	22.8	23.8	18.0	22.1	19.3
Rijal et al [1]	22.9	NA	23.4	NA	NA	20.9
Hong et al [17]	20.4	NA	21.0	18.9-19.1	NA	17.1-19.0

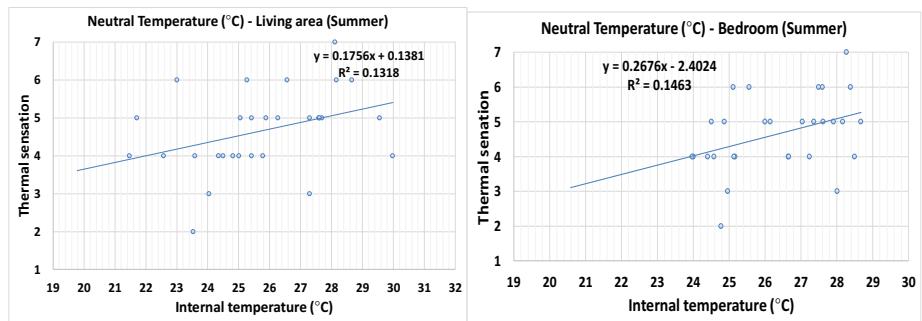


Figure 6: Relationship between thermal sensation and the internal temperature in the spaces in the summer

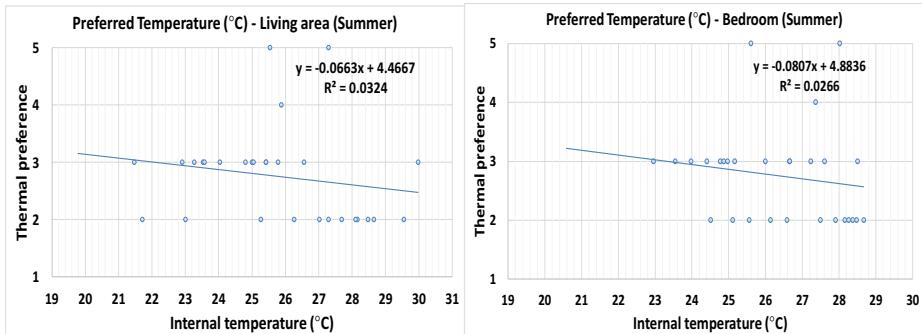


Figure 7: Relationship between thermal preference and the internal temperature in the spaces in the summer

### Possible causes and remedial measures to overheating

Since findings presented in this study revealed that overheating occurs in the dwelling, it is important to highlight possible causes and remedial measures to overheating. Some of the possible causes include reduced ceiling-to-floor height of the dwelling, reduced height and area of windows, and use of low performance windows in some of the spaces. Possible remedial measures include higher floor-to-ceiling height, use of high performance windows and doors, and application of passive cooling strategies. Also, improved thermal mass of building envelopes as mentioned in existing studies [4,11] and behavioural actions [6] can reduce overheating in dwellings. However, these remedial measures require further research to understand the extent the measures can reduce overheating in timber dwellings.

### Conclusions

This study evaluated occupant's comfort, summertime and wintertime temperatures in a timber dwelling. The study found that occupants feel warm in summer and slightly cool in winter. The subject votes revealed that the occupants prefer to be cooler in summer than they were with mean thermal preference votes in winter around thermal neutrality. However, occupants are thermally satisfied with the thermal environment. The results revealed over 80% of the respondents are comfortable within the thermal environment.

Higher mean (summer – 0.5°C, winter – 0.7°C), neutral (summer – 1.8°C, winter – 0.8°C) and preferred (summer – 1.1°C, winter – 2.6°C) temperatures are observed in the bedroom than the living area in the summer and winter. The mean temperatures are also higher than the mean temperature (19.1°C) recorded in a study conducted in UK dwellings in 2001 [18]. The bedroom is found to be warmer than the living area. This finding is in agreement with the finding presented in existing studies [4,15]. Comparing the findings from this study to existing research, temperatures especially neutral and mean temperatures are slightly higher than temperatures reported in existing studies. The findings showed timber buildings are prone to summertime temperatures and possibly

lower wintertime temperatures. Also, occupants living in timber dwellings are likely to develop higher adaptability to the thermal environment than those living in other dwellings.

Overheating is likely to occur at a frequent rate in the bedroom than the living area of the timber dwelling. Over 7% of the hours rose above the 28°C and the BSEN15251 Category II upper limit when measured temperatures are evaluated in the living area using the CIBSE and the adaptive comfort models. Extreme summertime temperatures (18% of the hours above the 26°C indicator) and warm discomfort (15% of the hours above the BSEN15251 Category II upper limit) are also reported in the bedroom.

Finally, this study revealed possibility of temperatures to be extreme in timber dwellings in summer. However, the findings showed occupants tend to be more comfortable with thermal environment and no overheating is reported in winter. From this study, it appears the occupants preferred higher temperatures in the summer and winter in the bedroom than the living area. This is a crucial finding that needs to be investigated in further research to understand occupants' comfort in the sleeping area since timber has low thermal mass which may affect or influence occupants' comfort in timber dwellings.

## References

- [1] Rijal, H.B., Stevenson, F. (2010). Thermal comfort in UK housing to avoid overheating: lessons from a 'Zero Carbon' case study. In *Proceedings of Windsor Conference*, Cumberland Lodge, UK, 9 – 11 April, 2010.
- [2] Gupta, R, Gregg, M. (2013). Preventing the overheating of English suburban homes in a warming climate. *Building Research & Information*, 41, pp. 281-300
- [3] Lomas, K.J, Kane, T. (2013). Summertime temperatures and thermal comfort in UK homes. *Building Research & Information*, 41, pp. 259-280
- [4] Adekunle, T.O., Nikolopoulou, M. (2016). Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Building and Environment*, 103, pp.21-35
- [5] Adekunle, T., Nikolopoulou, M. (2014). Post-occupancy and indoor monitoring surveys to investigate the potential of summertime overheating in UK prefabricated timber houses. In *Proceedings of Conference: Counting the Cost of Comfort in a changing world*, Cumberland Lodge, Windsor, UK, 10 – 13 April, 2014
- [6] Morgan, C., Foster, J.A., Poston, A., Sharpe, T.R., (2017). Overheating in Scotland: contributing factors in occupied homes. *Building Research & Information*, 45(1-2), pp. 143-156
- [7] Rijal, H.B. (2013). Field investigation of comfort temperature and adaptive model in Japanese houses. In: *PLEA 29<sup>th</sup> Conference*, Munich, Germany, 10 – 12 September, 2013.
- [8] Department for Business, Energy & Ind. Strategy (2016). *Energy consumption in the UK*. DBEIS, Nov.
- [9] Environmental Protection Agency (EIA, 2015). *How much energy is consumed in residential and commercial buildings in the United States?* Available: <https://www.eia.gov/tools/>, accessed on 21/03/2017.
- [10] Adekunle, TO., Nikolopoulou, M. (2016). *Evaluation of prefabricated structural timber housing*. LAP Publishing, Germany.
- [11] Adekunle, T. O. (2014). *Thermal performance of low-carbon prefabricated timber housing in the UK*. PhD Dissertation, University of Kent, UK
- [12] CIBSE, (2006). *Guide A, Environmental Design*. 7th Edition, CIBSE, London
- [13] CIBSE, (2010). *How to manage overheating in buildings: a practical guide to improving summertime comfort in buildings*. CIBSE Knowledge Series. The Chartered Institution of Building Service Engineers, London.
- [14] BSEN15251, (2008). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels.
- [15] Sharpe, T.R., Porteous, C.D.A., Foster, J., Shearer, D. (2014). An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland. *Indoor Built Environ.* 23, pp. 393–416.
- [16] American Society of Heating, Refrigeration, and Air-conditioning Engineers (2013). *Standard 55-2013, Thermal Environmental Conditions for Human Occupancy*. ASHRAE. Atlanta, GA.
- [17] Hong, S.H., Gilbertson, J., Oreszczyn, T., Green, G., Ridley, I., the Warm Front Study Group (2009). A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment*, 44(6), pp. 1228-1236
- [18] Shorrock, L.D., Utley, J.I., (2003). *Domestic energy fact file 2003*. Building Research Establishment, Watford, UK



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Environmental Performance of the Engineering Science and Learning Centre UK: An investigation of thermal and light benefits from an atrium covered by ETFE cushions

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**Abstract:** Nowadays, Ethylene-tetrafluoro-ethylene (ETFE) cushion roof is being used substantially for covering atrium as an alternative to glass roof. This paper examined the environmental performance of the Engineering and Science Learning Centre (ESLC) at a university campus, investigating the thermal and luminous environment and the environmental benefits of the atrium covered by ETFE cushions on the adjacent learning spaces in the building.

This study was undertaken by using different analytical tools, which include environmental design rule of thumbs, field work and selective computer aided simulations using IES VE for parametric analysis of the existing and improved luminous and thermal environment. The users' perceptions of the light and thermal conditions were critically evaluated by using questionnaire and the results were correlated with the theoretical data obtained from the quantitative studies.

The research results show that the learning spaces have insufficient daylight illuminance towards the far end of the lecture rooms and the high illuminance level in the ETFE covered atrium is not benefiting the adjacent spaces. In addition, the learning spaces are out of comfort zone and have high CO<sub>2</sub> concentration for most of the time during summer due to the ineffective ventilation strategy with inadequate effective opening size of the roof vents. This study proposed and tested the alternative daylighting solution by modifying the window profile to the walls of the learning spaces facing the atrium, and developed new summer ventilation strategies to improve the thermal performance of the learning spaces adjacent to the atrium.

**Keywords:** ETFE Cushions, Environmental Performances, Daylighting, Thermal Comfort, Air Quality

### Introduction

Atrium is often used as a common architectural solution and environmental strategy to improve the internal conditions of buildings to bring more daylight into the inner space, transferring the light to the surrounding, acting as a buffer zone to prevent direct solar penetration and drive surplus heat (CIBSE, 2006). The building envelope has significant impacts on the indoor environmental conditions which can affect occupants' health and performance (Irene and Robert, 2007). Meanwhile, Glass has traditionally been used in atria to admit natural light and modify the indoor environment, but in recent years, ETFE has become an alternative to glass (Tanno, 1997).

A single ETFE foil transmits 94-97% of visible light, a higher percentage than the equivalent 89% of single glazing. A double layer ETFE transmits approximately 76% of visible light, which is similar to the amount of visible light transmitted by a typical double glazed unit (Robinson-Gayle et al., 2001). According to Tanno (1997), a standard 3 layer cushion has a U-value of around  $1.95 \text{ W/m}^2 \text{ }^\circ\text{K}$  which is considerably better than triple glazing when used horizontally.

This study examined the luminous and thermal environment of the ETFE enclosed atrium space of the Engineering and Science Learning Centre at the University of Nottingham and investigated how both daylight and thermal conditions in the atrium can be passively used to improve the indoor environmental conditions of the adjacent spaces. The atrium and two typical teaching spaces (Room B02, B13) on the first floor were chosen for detailed performative analysis and improvement.

## **Case Study and Seasonal Environmental Strategies**

### ***Engineering and Science Learning Centre***

The Engineering and Science Learning Centre (ESLC) is located at the north-east side of the University Park, University of Nottingham, UK. It is surrounded by the medium rise educational Buildings. It was designed by Hopkins Architects and completed in 2011. It is a  $3500\text{m}^2$  horseshoe-shaped, three-storey educational building accommodating students support office, graduate centre, offices, learning and teaching spaces and a multi-functional central atrium.

The ESLC atrium roof consists of three-layered ETFE cushions that bring top lighting into the atrium of the building and complimented by a glazed aperture on the southwest façade. On its south east elevation, it is cladded in horizontal aluminium louvers. Figure 1 and 2 show the building exterior and interior of the building.



Figure 1. Exterior views of ESLC



Figure 2. Interior views showing the atrium and ETFE roof

### ***Selected Studied Rooms***

The selected rooms are typical teaching spaces located on the first floor as shown in Table 1 and Figure 3.

Table 1. Geometric parameters of the selected rooms

Room	Orientation	Window area ( $\text{m}^2$ )	Floor area ( $\text{m}^2$ )	Window/floor ratio	Distance to nearby building
Room B02	Northwest	29	108	0.27	16m
Room B13	Southeast	15	54	0.27	9m

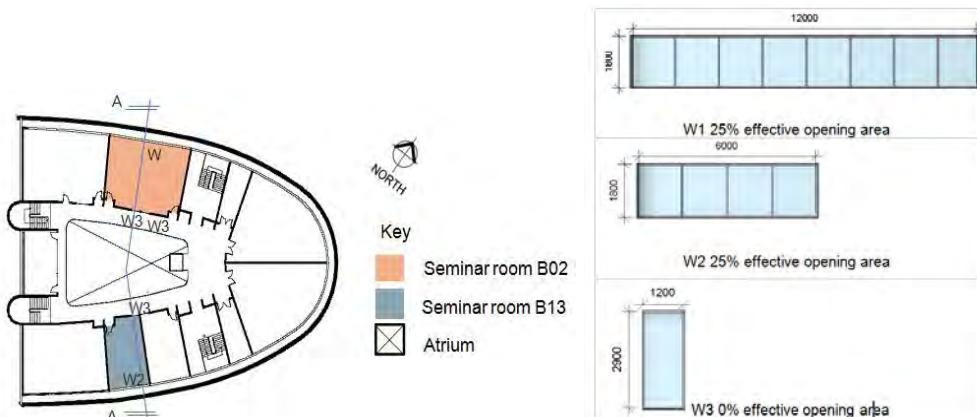


Figure 3. ESLC first floor plan showing the selected rooms and window schedule

### **Building Environmental Strategies**

The environmental control system for this building is a hybrid system, mechanical ventilation via AHU system provides cooling in summer, while in winter, closed loop ground source heat pump are used as a primary heat source with additional perimeter heating via fan coil units and under floor heating to the atrium area with reverse cycle for mechanical ventilation via AHU. The building environmental strategies are shown in Figure 4

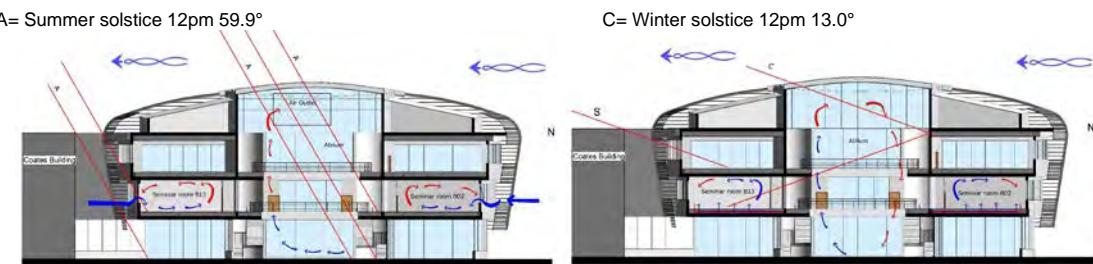


Figure 4. Summer and winter environmental strategy (Section A-A)

### **Building Users' Satisfaction**

The survey was conducted on site using 7 points scale questionnaire on 6th May, 2016 with outdoor temperature of 21°C. The questionnaire was answered by 18 students and their levels of satisfaction to the indoor environmental conditions were presented in Figure 5.

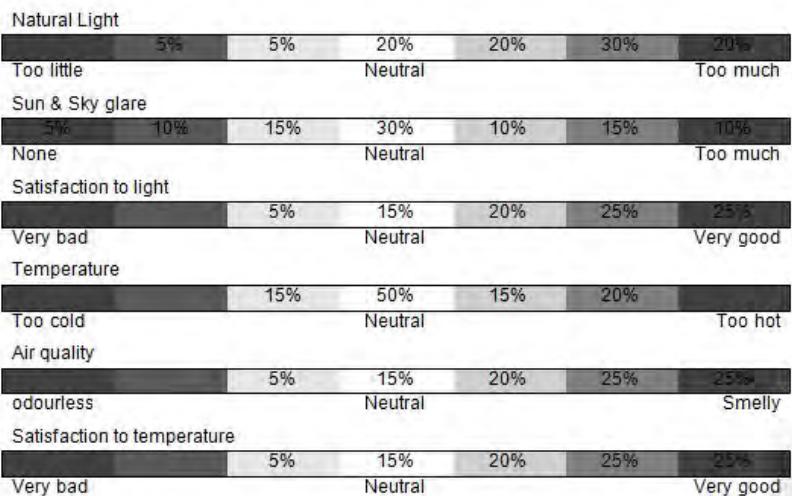


Figure 5. Building users indoor environmental conditions survey results

From the result of the survey, most participants, especially the ones in the atrium complained that there was too much light while users on the third floor of the atrium felt

that there was glare and the temperature was hot and air quality was neutral. The participants in the adjacent spaces were mostly neutral in their responses to natural light perception, but their view on the air quality was smelly.

## On-site Monitoring

### *Daylighting Performance Assessment*

The daylight spot measurements were carried out under sunny sky conditions by using an illuminance meter. The objective was to evaluate the daylighting performance in the atrium and to examine the daylight benefits from the atrium on the adjacent spaces.

### Results

The daylight illuminance in the central part of the atrium (Figure 6) was high and it decreased towards the atrium edges. The average internal illuminance at ground level was 12791 lux while the highest and the lowest value were 33180 lux and 4030 lux respectively compared to average external illuminance was 35698 lux. This indicated that the ETFE cushion transmitted about 93% of the outdoor illuminance into the atrium, which confirmed the abundance of daylight in the space.

The daylight illuminance in the learning spaces B02 and B14 were higher closer to external windows and reduced sharply from the window. In B02, the illuminance level decreased towards the atrium window, which indicated that the atrium did not benefit the luminous environment in the selected adjacent rooms (Figure 7).

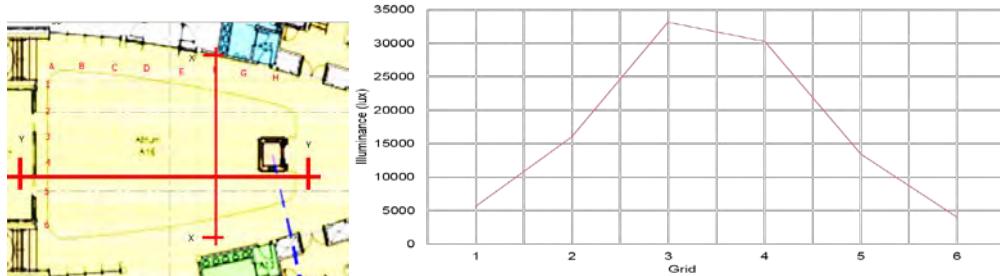


Figure 6. Atrium measurement grid plan and daylight illuminance distribution along Section x-x

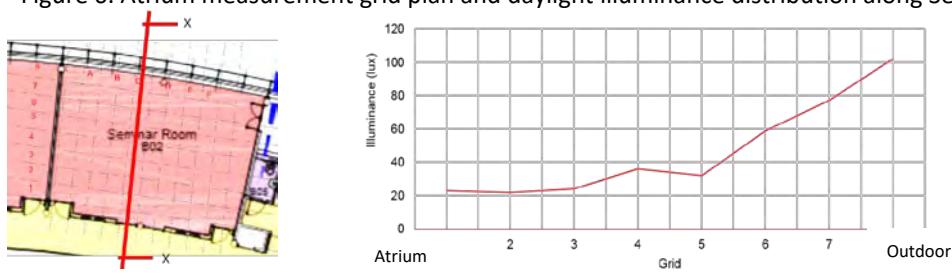


Figure 7. Room B02 measurement grid plan and illuminance distribution along Section x-x

### *Thermal Performance Evaluation*

The on-site monitoring was carried out to investigate the indoor thermal environment at each level of the atrium and the selected rooms. Temperature and CO<sub>2</sub> were taken simultaneously using tiny tag data logger while the surface temperatures were measured using Fluke infrared thermometer.

### *Results and Discussion*

The results of the thermal environment at different level of the atrium on Tuesday and Wednesday which are the days with full occupancy are shown in Table 2. The thermal image analysis of the atrium temperature variance is shown in Figure 8. During the day and night,

temperature stratification was observed in the atrium that is a potentially why the survey participants on the 3rd floor gave unsatisfactory remark on the temperature. The temperature and CO<sub>2</sub> concentration of the atrium space increased during the occupancy period and decreased at night as presented in Figure 9.



Figure 8. Thermal image of atrium showing temperature stratification

Table 2. Atrium temperature and relative humidity during the night and occupancy period (day)

Night (1 <sup>st</sup> March 2016, 22:00pm)					Day (2 <sup>nd</sup> March 2016, 12:00pm)			
Outdoor temperature=16°C			Relative Humidity 50%		Outdoor temperature=20.2°C			Relative Humidity 27%
Level	Space temp.(°C)	Wall (°C)	Floor (°C)	Ceiling (°C)	Space temp.(°C)	Wall (°C)	Floor (°C)	Ceiling (°C)
1	17.3	20	20.5	19.5	17.3	20	20.5	19.5
2	18.4	20.5	20.5	21	18.4	20.5	20.5	21
3	18.7	19.5	19.5	15.5	18.7	19.5	19.5	15.5

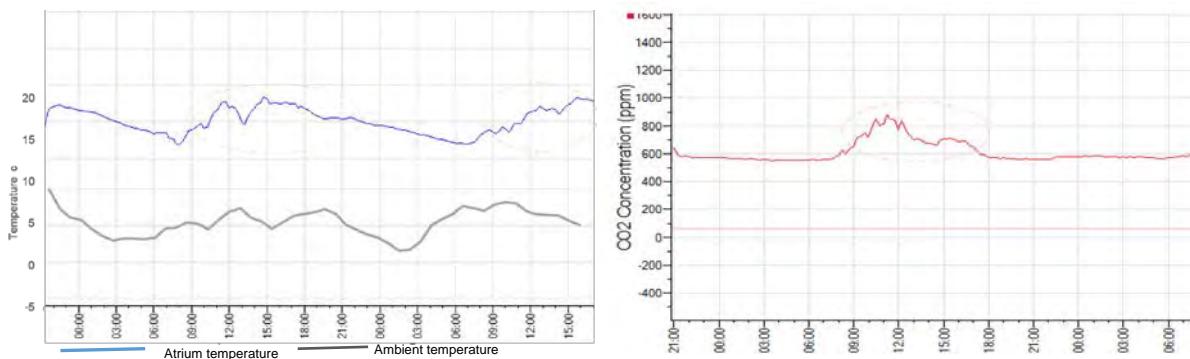


Figure 9. Atrium temperature and CO<sub>2</sub> concentration

It was observed from the result in Figure 10 that the indoor temperature of B02 is within comfort threshold during the occupied period. The CO<sub>2</sub> concentration reached 900ppm which is peak recommended level by the CIBSE to maintain comfort. The increase in occupancy level might result to the CO<sub>2</sub> concentration to rise more than the recommended level.

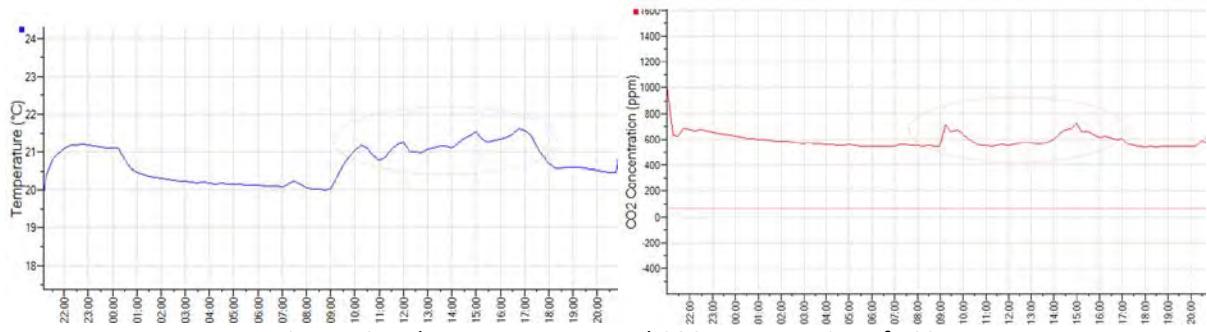


Figure 10. Indoor temperature and CO<sub>2</sub> concentration of B02

## Building Performance Predictions

### *Daylighting performance predictions*

The prediction of the luminous quality of the selected spaces was conducted with the objective of understanding the percentage of the time the learning spaces are naturally lit. This dynamic daylight simulation was undertaken by using IES VE with correct surfaces reflectance and the working plane was set at 850mm above finished floor level.

### *Results and Discussion*

The Spatial Daylight Autonomy (SDA) of this B02 showed that 51.23% of the floor area receives 300 lux for 50% of occupancy period. The SDA of B12 revealed that 18.24% of the floor area received 300 lux for 50% of occupancy hours (8:00-18:00) which is considerably low to IES benchmark of 50% floor area to admit 300Lux for 50% of occupancy time (IES,2012). The simulation results of B02 and B12 are presented in Table 3 and 4 respectively.

Table 3. Climate-based daylight prediction of B02

SDA: 300 lux 50 % (8:00-18:00)	DF for Overcast Sky	Annual Average Lux for DA	Annual UDI 100-300 Lux for DA
51.23%	Min. =0.6% Max. =16.4% Average =3.46% DF> 2% =44.12%	Min. =81.6 Max. =2251.2 Average =515.42	<25 =34.56% 25-50 =64.70% 50- 75 =0.74%

Table 4. Climate-based daylight prediction of B12

SDA: 300 lux 50 % (8:00-18:00)	DF for Overcast Sky	Annual Average Lux for DA	Annual UDI 100-300 Lux for DA
18.24%	Min. =1.4% Max. =12.4% Average =4.09% % DF > 2 =90.2%	Min. =182 Max. =1338.8 Average =508.32	<25 =17.65% 25-50 =82.35%

## Building Performance Improvements

### *Daylighting*

For improving the daylight benefit from the atrium to the adjacent rooms, three cases with three different window profiles were investigated. Figure 11 shows the window profiles, A is base case while B and C are the improved window profiles: case 1 and 2 respectively.

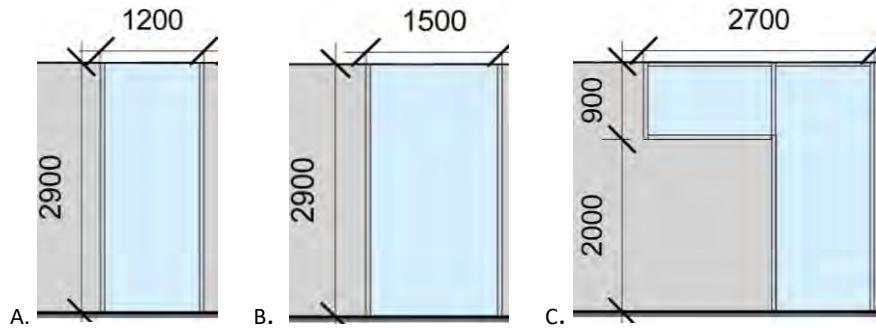


Figure 11. Window profiles for daylight improvements

### **Thermal and Air quality**

Using the internal windows facing the atrium as air outlets, cross ventilation of the adjacent rooms could be achieved as illustrated in Figure 12 and the simulation results are shown in Figure 13. Three cases of effective window opening were investigated to achieve good indoor environmental conditions. The following assumptions were made: Simulation period was in summer (May-August), occupancy period (8:00-18:00), occupancy density of 40 students, Laptop 15w/m<sup>2</sup>, projector 360w, light 2.2 w/m<sup>2</sup>, air exchange is natural ventilation with maximum flow of 10ACH, 30% air inlet and outlet effective opening (acoustic duct) is 30%.

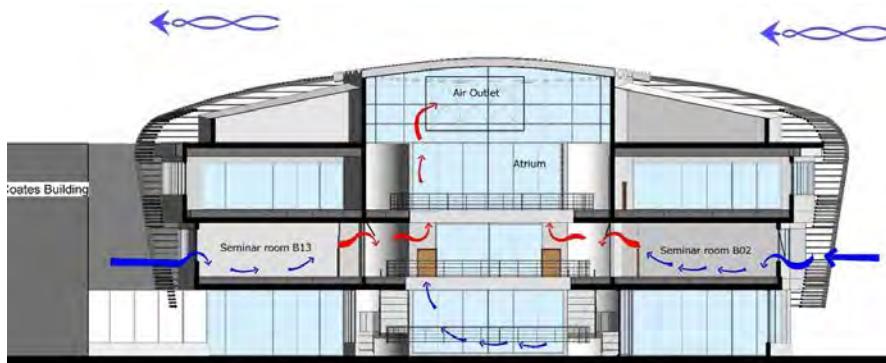


Figure 12: Summer strategy for thermal and air quality improvements

### **Results and Discussion**

In case 1 the percentage annual UDI of 100-300 Lux for DA of B02 increased by 6.15% while case 2 achieved 10.2% improvement to the existing condition. For Seminar Room B12, the percentage annual UDI of 100-300 Lux for DA increased by 2.7% for case 1 while case 2 resulted in 5.7% improvement to the UDI of the existing room. This implies the window profile C admits more daylight from the atrium space into B02. The day lighting improvement result is presented in Table 5 and Figure 13

Each simulation was presented in percentage of hours during summer when the temperature is within comfort band and CO<sub>2</sub> concentration is within 450ppm-650ppm. For B02, the percentage within comfort temperature increased to 69.5% in case 1 and 79.4% in case 2. Meanwhile the air quality improved from 44.5% to 80% for case 1 and 97.7% for the case 2. By adopting cross ventilation strategy, the atrium facilitated improvement in percentage of time within 450-650ppm by 35.6%. The air quality and the period within comfort level improved by 50.9% and 34.3% respectively for B12. The thermal improvement result is presented in Figure 14.

Table 5. Comparison of Percentage of annual UDI 100-300 Lux for Daylight Autonomy for all the cases

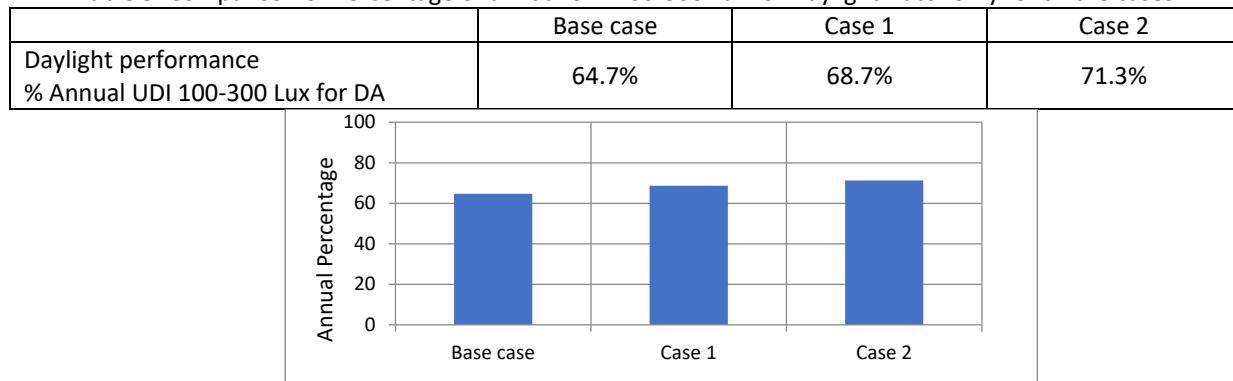


Figure 13. Percentage of annual UDI 100-300 Lux for Daylight Autonomy for all the cases

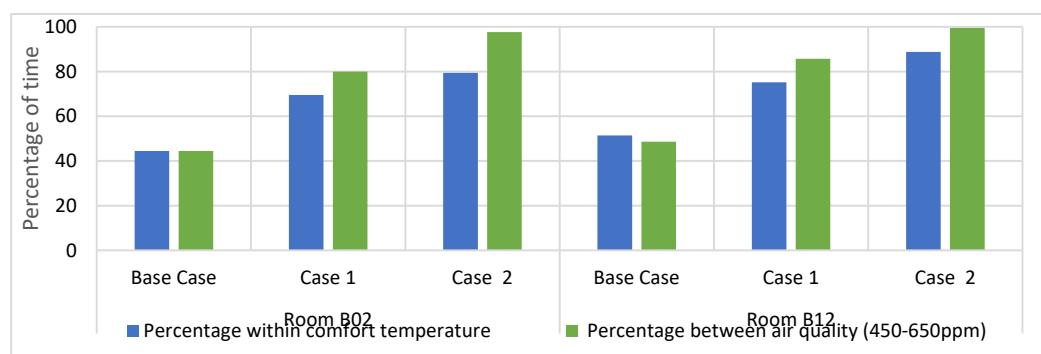


Figure 14. Percentage of time within comfort temperature and air quality

## Conclusion

In the current building, this study concluded that the atrium does not offer sufficient daylight benefits to the adjacent spaces. With proper window to wall ratio, the adjacent rooms could borrow light from the main atrium. There was temperature stratification in the atrium and occupancy density affected the temperature and air quality in the selected spaces.

The proposed atrium window options help improve the daylight level, the annual percentage of time within comfort temperature and desirable air quality. This paper concluded that through proper atrium window design, the thermal and luminous environment of the adjacent spaces facing the atrium can be significantly improved, and as a result, it is expected that overall energy consumption can be substantially reduced and the comfort conditions can be much improved.

## References

- CIBSE, 2006. Environmental design: CIBSE guide A. 7th edition, London: CIBSE: p. 2- 8.
- Illuminating Engineering Society, 2012. IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Newyork: LM-83-12.
- Irene, L. and Robert. T., 2007. Examining the role of building envelopes towards achieving sustainable buildings. Glasgow, UK, International Conference on Whole Life Urban Sustainability and its assessment.
- QTC Projects, 2016. University of Nottingham Estate Office. Available at: <https://www.nottingham.ac.uk/estates/documents/spaceresource/poe-engineeringsciencelearningcentre.pdf>
- Robinson-Gayle, Kolokotroni, Cripps & Tanno, 2001. ETFE foil cushions in roofs and atria. *Construction and Building Materials* 15(7): 323- 327.
- Tanno, S., 1997. Etfe Foil Cushions as an alternative to glass for atriums and roof lights. Bath, United Kingdom, ICBEST Conference on Building Envelope Systems & Technology.



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*Design to Thrive*

## Evaluating indoor environmental performance of laboratories in a Northern Nigerian university

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**Abstract:** Poor environmental comfort in learning spaces can have an impact on the learning capacities of students. It is not unusual to find learning spaces in Nigerian higher institutions in which the indoor environmental qualities do not meet the occupants' requirements. Despite being in the tropics, where solar radiation is in abundance, Nigerian building industry professionals pay little attention to passive energy utilization. Knowing how buildings perform in the country may appeal to their consciousness in reconsidering this situation. This paper is part of an ongoing study on comfort in higher education facilities involving lecture theatres and laboratories in Bayero University, Kano, Nigeria. Objective and subjective assessments were undertaken during the wet-warm season of August 2016. It reports the assessment conducted on two laboratories, with a view to finding how they perform environmentally in comparison to occupants' preferences and international comfort standards. Although some of the measured and calculated physical parameters, have not met the thresholds specified by ASHRAE-55 and EN 15251, the respondents expressed their acceptance of the laboratories' situations subjectively. This is not surprising as these standards are often based on experiments implemented in developed countries, where the severity of the climatic conditions and the culture are dissimilar to sub Saharan Africa.

**Keywords:** IEQ, Predicted Mean Vote, Predicted Percentage of Dissatisfied, Kano, Nigeria

### Introduction

Indoor environmental quality (IEQ) investigations in several buildings, such as offices, hospitals, schools and shopping malls, have been on the increase since the middle of the last century. Such an increase in the studies could be attributed to the concern of the adverse effect poor IEQ has on people's comfort and wellbeing, which potentially affects their productivity and performance (Dias Pereira et al., 2014; Heath & Mendell, 2002). As vividly captured by Almeida (2014), that it is the combination of rising indoor occupancy levels, health requirements, environmental concern, new construction practices, rising occupants' expectations, development of new indoor finishes and the desire to cut down on energy costs that led to the need of the IEQ studies. Similarly, the need to contribute to the effort of decreasing global warming in reducing energy consumption from fossils sources has led to the rise in such types of studies.

Many studies have been evaluating IEQ and analysing indoor conditions through investigating the thermal, visual and aural environments as well as indoor air quality (IAQ) (Catalina & lordache, 2012; Frontczak et al., 2012; Nimlyat & Kandar, 2015). Frequently reported poor IEQ concerns include discomfort due to high or low temperatures and relative

humidity; high level of carbon dioxide concentration ( $\text{CO}_2$ ), carbon monoxide (CO), volatile organic compounds (VOCs) and PM; inappropriate lighting levels and presence of glare and occurrence of noise. Poor thermal environment affects occupants' mental performance as well as increasing stress and fatigue among them (Auliciems, 1972). Appropriate quality and quantity of light are important to building occupants' health and wellbeing, affecting their mood, emotion and mental alertness (Salonen, 2013). Acoustic discomfort is shown to cause fatigue, headaches, annoyance, changes in behavior and attitude leading to decrease in intellectual working ability and sleep disorders (Hodgson, 2000). High level of PM was reported to increase respiratory symptoms and acute lung diseases in schools (Rumchev, 2003). Raised concentrations of  $\text{CO}_2$  is also associated with morbidity, absenteeism in school children and office workers (Valavanidis & Vatista, 2006).

Although IEQ studies including those in higher education institutions are on the increase, most of the published works deal with buildings located in temperate climate zones and mainly situated in wealthier parts of the world, and not in Sub Saharan Africa. Some examples of researches conducted in higher education buildings include (Al-Maiyah et al., 2015; Mishra & Ramgopal, 2013; Ogbonna & Harris, 2008; Ugranli et al., 2015).

Furthermore, most of the studies in higher education facilities tend to concentrate on classrooms, lecture theatres, libraries, offices, students housing, and fewer works were done on laboratories (Rumchev, 2003). The few articles published on laboratories were mostly concerned with a single aspect of the IEQ, which is IAQ. Rumchev et al., (2003) investigated 15 laboratories at the Curtin University of Technology, Perth, Australia. Ugranli et al., (2015) investigated IAQ and two comfort related variables (air temperature and relative humidity) in chemistry and chemical engineering laboratories at Izmir Institute of Technology, Turkey.

This paper therefore reports the assessment conducted on two laboratories, with a view to finding how they perform environmentally in comparison to occupants' preferences and international comfort standards. Environmental parameters were physically measured while a sample of students completed paper based questionnaires on comfort parameters.

## **Methodology**

### ***Description of the research location***

Bayero University (BUK) is a conventional university, situated in Kano, Nigeria. Kano is located on latitude  $12^{\circ}\text{N}$  and longitude  $8.17^{\circ}\text{E}$ , 473 m above sea level and in the savannah vegetated region of West Africa. Maximum temperature reaches  $39^{\circ}\text{C}$  in April and May and goes down to  $12^{\circ}\text{C}$  in December and January and it is sunny 71% of the daylight hours (climatetemp.com, 2017). Relative humidity hovers between 10% and 80% and the annual precipitation is about 700 mm. As with other parts of Nigeria, the city is faced with the problem of perennial haze/dust blown in November to February from Sahara desert.

BUK has about 30,000 students admitted within 14 faculties, undergoing various programmes from three campuses spread across the city of Kano. From the last eight years the university's landscape has been transforming by adding new structures and retrofitting existing ones. The selected laboratories for the study were chosen from the Old campus and Teaching hospital. These are, Multipurpose Laboratory (ML), used for approximately 30 hours per week by Science faculty for their level 100 undergraduate students and Phantom Laboratory (PL), used for about 18 hours per week, by the clinical students of Dentistry faculty. The characteristics of the laboratories are shown in Table 1.

Table 1: Characteristics of the Laboratories

Attributes	Multi-purpose Laboratory (ML)	Phantom Laboratory (PL)
Capacity	120 seats	40 seats
Length x width x height	20 m x 15.50 m x 3.27 m	17.8 m x 7.3 m x 3.48 m
Occupancy density	2.58 m <sup>2</sup> /person	3.25 m <sup>2</sup> /person
Wall finishes	Light paint on cement plaster	Light paint on cement plaster
Ceiling finish	White Celotex acoustic boards	White Celotex acoustic boards
Area of glazing	41.86 m <sup>2</sup> (no blinds)	19.80 m <sup>2</sup> (has internal blinds)
Glazing factor	15.76%	15.24%
Number of window-walls	Three	Two
Window-walls orientations	South, East and North	West and East
Window-wall area ratio	South 23%, East 20% and North 15%	West 16% and East 16%
Type of furniture finish	Metal/wood tops and soft seats	Metal/wood tops and soft seats
Presence and type of shading	Shaded by fins	Internal blinds and one sided verandah

### Physical Measurement

Both the physical measurements and the surveys were conducted based on procedures consistent with ASHRAE standard 55-2013. A number of instruments were used to measure the indoor environmental parameters. The spot measuring instruments were simple and hand held. They include HOBO loggers for air and radiant temperatures, relative humidity, carbon dioxide (CO<sub>2</sub>) concentration, and illumination; Trotec BZ30 for air temperature, relative humidity and CO<sub>2</sub> concentration; Testo 435-2 meter for air velocity; PCE-DT 9880 for particulate matter (PM) and Extech HD600 meter measures sound pressure levels.

Temperature, relative humidity, air velocity, sound pressure levels and CO<sub>2</sub> concentration, using the hand held instruments by the researcher, were spot measured in five locations, each for five minutes and at 1.1m above the floor. Whereas illumination levels were spot measured in nine locations at the same height. Daylight was obtained when electric lights were off and window blinds opened. Photographs of the interiors of the laboratories and points of measurements are marked on the floor plans shown in Figures 1 and 2. Though air conditioners were not in operation, ceiling fans were on most of the time and windows opened. Measurements were conducted in two situations, during occupied and unoccupied conditions. External weather data were obtained using pendants on the buildings' exteriors.



Figure 1: Multipurpose Lab. (ML)

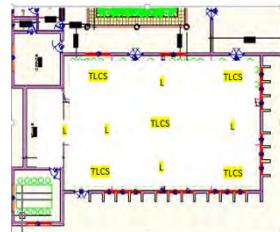
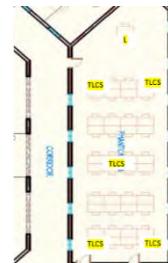


Figure 2: Phantom Lab. (PL)



NOTATIONS: T: Temperature; L: Lighting; C: Carbon dioxide concentration; S: Sound

### Subjective Measurement

In line with the capacities of the laboratories, a total of 160 paper based questionnaires were prepared, for the occupants to answer. It contains six sections covering; thermal, acoustic and visual comfort, indoor air quality and demographic information. In addition, sketches of the respective learning environments were included for the occupants to indicate their approximate sitting positions. A total of 105 questionnaires (86 and 19 for the ML and PL

respectively) were subsequently distributed, filled and collected back. The surveys were administered between 12 noon and 12:30 pm on 22<sup>nd</sup> August 2016 in the PL, while in the ML it took place on 29<sup>th</sup> August 2016 at 10:45 am. The questionnaires were answered by the students, teachers and support staff.

Typical questions on the parameters took the form of: how comfortable are you with thermal condition of this space now? How would you describe the temperature, natural and artificial lighting, noise and odour in this space? Responses required by these questions were made on a mixture of categorical (e.g. acceptable and unacceptable; comfortable and uncomfortable) and seven point Likert scales between two extremes; cold and hot; satisfactory and unsatisfactory; too much and too little; significant and not significant; pleasant and unpleasant, following the methods used in previous studies (Ai Maiyah et al., 2015; Montazami et. al., 2016).

Similarly a list of typical clothing ensembles worn by the respondents in the environment was provided for them to indicate the ones they had on. Thermal sensation vote was to be expressed on the ASHRAE standard 55 seven-point scale (e.g. cold, cool, slightly cool, neutral, slightly warm, warm and hot). This allows the evaluation of "actual mean vote" (AMV) and the dispersion regarding the "actual percentage of dissatisfied" (APD). These were compared with the Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

Table 2: Measured Internal Parameters

Laboratories		Air Temperature (°C)		Relative Humidity (%)		Illumination (lux)		CO <sub>2</sub> Concentration (ppm)		Background Noise dB(A)		Air Velocity (m/s)		Particulate Matter (per m <sup>3</sup> )	
		Unoccupied	Occupied	Unoccupied	Occupied	Day-light	Global	Unoccupied	Occupied	Unoccupied	Occupied	Fans off	Fans on	PM 2.5	PM 10
Multi purpose	Min	28.1	31.0	71.6	61.4	78	131	602	633	50.0	54.2	0.18	0.28	179	17
	Max	28.5	31.7	74.8	66.5	456	586	807	1028	50.4	62.3	0.21	0.34	222	48
	Mean	28.3	31.5	72.9	64.2	235	262	750	784	50.3	57.1	0.20	0.31	186	31
Phantom	Min	24.1	25.1	68.1	66.7	81	181	593	654	48.9	59.0	0.12	0.34	130	15
	Max	24.4	25.6	68.8	70.7	221	386	660	884	51.0	60.8	0.17	0.43	150	25
	Mean	24.3	25.3	68.4	68.8	188	286	627	727	50.0	59.7	0.15	0.40	139	17
Standards' Limits and ranges	24.5°C-28°C Summer 23.3°C-25.5°C winter (ASHRAE-55)		30-60% (ASHRAE-55)		500 lux for laboratory (EN-12464)		1200 ppm for any learning environment (ASHRAE 62-2004)		40-45dB(A) for laboratory (WHO 2006)						

Finally, demographic data of the participants was requested for the determination of their personal characteristics, which helped in developing appropriate summary statistics. In order to eliminate the impact of metabolic rate on the respondents, the questionnaires were administered in each space after 30 minutes into the laboratory sessions, adopted from previous study (Montazami et al., 2016). Similarly lighting, acoustic and air qualities parameters were evaluated on categorical and seven point Likert scales.

## **Results and Discussion**

International comfort standards' recommendations offered by ASHRAE Standard-55 2013 and EN 15251 and the grouping method followed by Almaiyah et al. (2014) were used for the evaluation of the laboratories' indoor environmental conditions. Thermal and visual comfort parameters were evaluated through both subjective and objective means. Likewise noise level was evaluated by measuring the background noise level and by asking the occupants about their aural perceptions. Indoor air quality was adjudged by measuring CO<sub>2</sub> concentration, PM<sub>2.5</sub> and PM<sub>10</sub>. It is worth noting here that, in this study however, only the singular values of PM<sub>2.5</sub> and PM<sub>10</sub> were used due to instrument limitation. The maximum, minimum and mean of the measured internal parameters as recorded during the survey are displayed in Table 2.

### **Measured Results**

Due to the differences in dates and times of measurements and the occupation situations, the air temperatures during the occupied time were generally higher, reaching 31.7 °C and 27.6 °C for ML and PL respectively. The reverse was the case with relative humidity, in ML it was higher when the space was unoccupied, reaching 74%, while the occupied figures stood at 66.5%. As with air temperature, the relative humidity in the PL was higher during the occupied time, reaching 70.7%. Air speed reached 0.34 m/s with fans on and windows opened in ML but was 0.45 m/s in PL. This variation could be as a result of the differences in the siting of the laboratories, as well as their design features and varied occupancy levels.

Light distribution in the laboratories was uneven, some locations in ML had as low as 78 lux natural lighting and 456 lux by the windows, with uniformity ratio (Emax/Emin) of 5.8:1. The daylight situation in PL was a little better, has uniformity ratio of 4.8:1. This could be due to the differences in the laboratories' compactness ratios. Differences exist in background noise levels in the laboratories, in ML had 62.3 dB(A) when occupied and PL 60.8 dB(A). Perhaps this could also be due to the location where PL was sited, being more isolated.

CO<sub>2</sub> concentration during the occupied time reached up to 1028 parts per million (ppm) in ML and was halved when unoccupied, while in PL it was only 884 ppm. These however did not exceed the ASHRAE 62's threshold value of 1200 ppm. PM<sub>2.5</sub> and PM<sub>10</sub> values respectively were 222 and 48 particles per m<sup>3</sup> in ML, but at some points they went as low as 179 and 17 particles per m<sup>3</sup>. However, these values were considerably lower in PL, which might be due to frequent use of chemicals in ML and less in PL.

### **Survey results**

The survey revealed that females accounted for 47% of the respondents, 94% were students and 89% were below the age of 25. From the clothing ensembles, clo values of 0.67 and 0.71 were calculated for ML and PL respectively (with a range of 0.5 to 0.85 clo). Metabolic rate for laboratory activity was fixed at 1.4 met (Tyler, 2013).

Generally the thermal perception in both laboratories was adjudged acceptable. From Figure 3, about two thirds of the respondents in ML reported that the space was comfortable and no one found PL uncomfortable. Despite this general acceptance, still some 8% and 21% of the respondents reported that the laboratories were "hot" or "too hot". In Figure 4, 41% and 0% reported they were "cold" or "too cold" in ML and PL respectively.



Figure 3: Thermal Acceptability

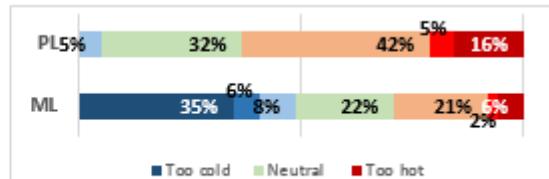


Figure 4: Thermal Sensation

On the quality of visual environment, 65% and 95% of the respondents in ML and PL respectively expressed their satisfaction with the global lighting levels as depicted in Figure 5. Similarly, only 21% and 22% reported that natural light was excessive and 23% and 17% said it was too little in ML and PL respectively. On the other hand, report on the level of glare perception as shown in Figure 6, was generally favourable, only 8% and 0% of the respondents perceived too much glare in the respective laboratories.

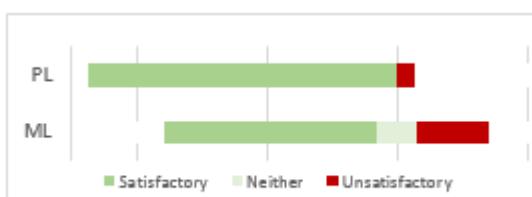


Figure 5: Global Visual Satisfaction

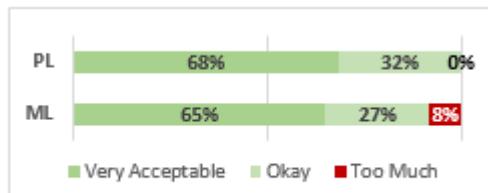


Figure 6: Glare Perception

Acoustically, the respondents showed very good satisfaction with the laboratories' background noise levels, only about 12% of those in ML showed their dissatisfaction, as depicted in Figure 7. It was concluded from the responses that the main sources of the acoustic discomfort in the ML were noise generated by their colleagues, this was reported by 43% of the respondents, while 25% of them said it was by external noise intrusion probably from traffic, as the lab is sited close to students' parking area.

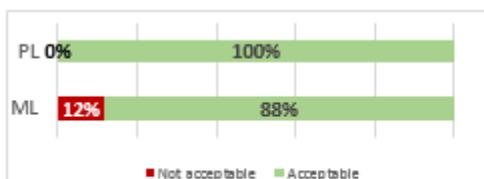


Figure 7: Background Noise Acceptability

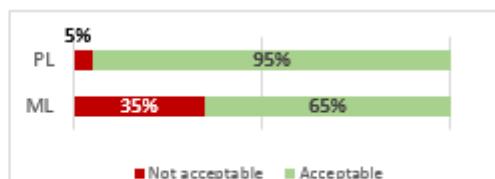


Figure 8: Air quality perception

Similarly the survey examined the respondents' perception about the quality of air in the laboratories. Figure 8 shows that there was general acceptability in the quality of air in ML, 65% attested to that, while 35% of them did not. Sources of the mild discomfort within the laboratory might be as a result of frequent use of chemicals, smoke rising from Bunsen burners, human effluents due to high occupancy level and absence of fume cupboards. However, there was an overwhelming acceptance of the air quality within PL, with as much as 95% of the respondents agreeing and only 5% showed their dissatisfaction.

## Comparison

Values of Fanger's PMV and PPD on the survey date, running mean, and operative and comfort temperatures for the laboratories were calculated. The values of the PMV stood at

+1.43 and +0.79 while PPD results were 47% and 18% respectively for ML and PL. These values indicate that the overall thermal sensation in both laboratories was warm, as laid out in the provisions of ISO 7730 (ISO, 2005). On the other hand, the AMV from the survey reported mixed perceptions, with -0.81 (cool) and +0.95 (warm) in ML and PL respectively. This therefore calls for further study. However, the calculated comfort ranges, according to EN 15251 (CEN, 2007) for buildings type II in ML, stood at 25.1°C to 31.1°C, while in PL it was 25.2°C to 31.2°C. This signifies that EN 15251 could perfectly be used in predicting thermal conditions in Kano, as reported by Mishra and Ramgopal (2015).

According to EN 12464 standard (CEN, 2011), global lighting levels in laboratories should be above 500 lux. The lighting situations in both laboratories were therefore insufficient, having averages of 262 and 286 lux. However, the survey results indicated otherwise. More than two thirds of the respondents were happy with the global lighting situations in both laboratories. Having higher lux and with greater percentage of respondents showing more satisfaction with the global lighting situations in PL, it revealed that PL was visually a preferred space. This could be attributed to PL's compactness, window height above the floor and the presence of high furniture in ML that restricts the passage of daylight.

Measurement revealed that the highest CO<sub>2</sub> concentration of 1028 ppm was found in ML, although it seemed high, it was however within the limit specified by ASHRAE 62, which is above 1200 ppm. Although the CO<sub>2</sub> concentrations in both laboratories were within the ASHRAE threshold, yet about one third of the respondents in ML reported their dissatisfaction and 5% in PL. This showed the subjectivity of comfort, which concurs with findings of Ugranli et al., (2015). The average background noise levels of 57.1 dB(A) and 50.0 dB(A) respectively found in ML and PL, though seemed low, but were found to be higher than the limit of 35 dB(A), as laid out by WHO (WHO, 1999). On the contrary, the respondents indicated their acceptance of the situations, only 12% of them were not satisfied with the aural conditions in ML, while 11% were undecided in PL.

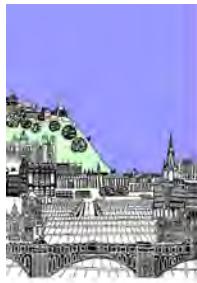
## Conclusion

The study, aimed at investigating IEQ in two laboratories in Bayero University, Kano, Nigeria, was conducted during the wet-warm season of August 2016. The scope included the comparison between experimental and surveyed data of the laboratories as well as against thresholds of relevant international comfort standards. Various physical parameters were measured which culminated into calculating some comfort indices. Concurrently, the occupants of the laboratories were subjected to a survey to determine their actual comfort perceptions. In line with the results obtained by some previous IEQ researches, this study, though part of a larger and longitudinal field work, also found discrepancies between measured and surveyed data, as well as with the comfort standards. Generally the results of the measured parameters were found to be higher than most of the standards thresholds with exception of CO<sub>2</sub> concentration. This divergence may not be unconnected with the situations of the dominant climatic conditions of the region at the time of the work. However, the survey data results showed acceptance of the indoor conditions of the laboratories by the respondents. Both the measured and the surveyed data of the PL were more consistent and acceptable to the respondents than those of the ML. This disparity may be explained by the compactness of PL and the siting of the two laboratories. PL is sited at the Teaching Hospital campus, though within the heart of the city, it is placed deep inside the campus and therefore buffered from the city traffic. ML, on the other hand, is sited at the Old campus and very close to the students housing parking area. It is therefore worth noting that good siting,

compactness, wide and operable windows as well as control of occupancy levels need to be taken into consideration when setting up a laboratory in the tropics.

## References

- Al-Maiyah, S., Martinson, B., & Elkadi, H. (2015). *Post Occupancy Evaluation of Daylighting and the Thermal Environment in Education Building*. Paper presented at the Passive and Low Energy Architecture (PLEA) 2015, Bologna, 09/09/2015. Retrieved from <http://plea-arch.org/plea-proceedings/>
- Auliciems, A. (1972). Classroom Performance as a Function of Thermal Comfort. *International Journal of Biometeorology*, Vol 16, No. 3, 233-246.
- Catalina, T., & Iordache, V. (2012). leq Assessment on Schools in the Design Stage. *Building and Environment*, 49, 129-140. <http://dx.doi.org/10.1016/j.buildenv.2011.09.014>
- CEN. (2007). *EN 15251:2007: EN 15251:2007 Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*. Brussels.
- CEN. (2011). *BS 12464-1-2011: Light and Lighting Lighting of Work Places Part 1 Indoor Work Places*: BSI.
- Climateps.Com (Producer). (2017, March 9). Weather and Climate. *climatemp.com*. Retrieved from <http://www.climatemp.com>
- Dias Pereira, L., Raimondo, D., Corgnati, S. P., & Gameiro Da Silva, M. (2014). Assessment of Indoor Air Quality and Thermal Comfort in Portuguese Secondary Classrooms: Methodology and Results. *Building and Environment*, 81(0), 69-80. <http://dx.doi.org/10.1016/j.buildenv.2014.06.008>
- Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., & Wargocki, P. (2012). Quantitative Relationships between Occupant Satisfaction and Satisfaction Aspects of Indoor Environmental Quality and Building Design. *Indoor Air*, 22(2), 119-131.
- Heath, G., & Mendell, M. J. (2002). *Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature*. Paper presented at the Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Indoor Air 2002.
- Hodgson. (2000). Experimental Investigation of the Acoustical Characteristics of University Classrooms. *Journal of Acoustical Society* Vol. 106, 1810-1819.
- ISO. (2005). *ISO 7730:2005: Ergonomics of the Thermal Environment — Analytical Termination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*.
- Mishra, A. K., & Ramgopal, M. (2013). Field Studies on Human Thermal Comfort - an Overview. *Building and Environment*, 64, 94-106. <http://dx.doi.org/10.1016/j.buildenv.2013.02.015>
- Nimlyat, P. S., & Kandar, M. Z. (2015). Appraisal of Indoor Environmental Quality (leq) in Healthcare Facilities: A Literature Review. *Sustainable Cities and Society*, 17, 61-68. <http://dx.doi.org/10.1016/j.scs.2015.04.002>
- Ogbonna, A. C., & Harris, D. J. (2008). Thermal Comfort in Sub-Saharan Africa: Field Study Report in Jos-Nigeria. *Applied Energy*, 85(1), 1-11. <http://dx.doi.org/10.1016/j.apenergy.2007.06.005>
- Rumchev, K., Van Den Broeck, V., & Spickett, J. (2003). Indoor Air Quality in University Laboratories. *Environmental Health*, Vol. 3, No. 3, 11-19.
- Salonen, E. A. (2013). Physical Characteristics of the Indoor Environment That Affect Health and Wellbeing in Healthcare Facilities: *Intelligent Buildings International*, 3-25.
- Tyler, H., Stefano, S., Alberto, P., Dustin, M. & Kyle, S. (2013). Cbe Thermal Comfort Tool. Berkeley: Center for the Built Environment, University of California Berkeley,.
- Ugranli, T., Toprak, M., Gursoy, G., Cimrin, A. H., & Sofuooglu, S. C. (2015). Indoor Environmental Quality in Chemistry and Chemical Engineering Laboratories at Izmir Institute of Technology. *Atmospheric Pollution Research*, 6(1), 147-153. <http://dx.doi.org/10.5094/Apr.2015.017>
- Valavanidis, A., & Vatista, M. (2006). Indoor Air Quality Measurements in the Chemistry Departmentbuilding of the University of Athens. *Indoor and Built Environment*, 15, 595-605.
- Who. (1999). Guidelines for Community Noise. Geneva: WHO Headquarters.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Measuring and presenting real time environmental indicators for optimised building performance

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**Abstract:** Building stock upgrade regarding both rebuilding and retrofitting has significant scope for emissions and energy reduction. Rebuilding may be favoured because of higher confidence in stricter current regulations than original. Retrofitting is more cost effective because of lower economic implications, faster turnaround times and less occupant disturbance. Retrofitting is possible at similar or higher level than legislation mandates but needs to be empirically proven. One method is to pervasively sense indoor conditions before and after retrofit. Comparisons can then made after compensating for weather conditions during monitoring periods. Independently developed calibrated dynamic simulation models can be used to benchmark expected performance improvements. Results may be relayed to interested parties in a format easily understandable by personnel not cognizant of building physics. This approach was deployed for buildings located in Greater Glasgow and managed by Glasgow City Council (GCC). Internet of Things technology was used for capturing data related to weather parameters, internal temperatures and humidity levels. Quantitative results and qualitative high-level observations were encapsulated within a software tool; training in use of which gave the Council means to independently and confidently assess quality of retrofit implemented by their contractors.

**Keywords:** Retrofit, Internet of Things, Pervasive Sensing, Modelling

### Introduction

The European building stock presents tremendous potential for reducing emissions and energy use. Another encouraging factor is that a major proportion was built before energy efficiency was fully introduced in building standards and consequentially presents a large room for improvement. Energy and emission benefits that can be realised by retrofit and rebuild – collectively called upgrading – for reduction of energy use also provide encouragement for economic growth in this sector. Resolution of the issue involves disciplines of building science, statistics, economics and social science and knowledge of trends in governmental guidelines and initiatives. Pilot projects have shown promise but technological and social barriers are such that successful upgrading efforts need to satisfy a large number of multivariate and often conflicting requirements. Consequentially quality of upgrading may be compromised thereby undermining the whole process.

It has been shown that upgraded buildings have lower embodied energy and can perform almost as well as new homes (Boardman et al., 2005). However, previous studies and findings from monitoring of upgraded houses have shown it is unusual that desired outcomes are obtained (Hong et al., 2006). Reasons for these shortfalls range from policy issues to technical problems and misunderstanding of social behaviour.

Most building stock improvement mechanisms are sponsored by government initiatives that promote efficiency upgrades and renewable technologies (Clarke et al., 2008). However, effective implementation is tricky because of large variability in age, composition, quality of build and use. Novel technologies such as distributed local renewable energy and fuel generation, smart grids and carbon capture methods are rapidly evolving. These may have a direct effect on energy performance of buildings but have not been well researched and established yet. There are gaps within existing upgrade practices with lack of skills and training being quoted often.

Although there have been some successes (URL 1) a large number of projects fall short of expectations. Negative outcomes have serious implications because the amount of investment and projected returns are large e.g. the estimated return for the US is \$1trillion over 10 years (Rockefeller Foundation and Deutsche Bank Group 2012). Similarly, Ernst & Young (2010) have estimated between \$25 and \$99 million in total economic activity in New South Wales. Figures for Europe can be expected to be comparable if not higher because it has a much older building stock than either of Australia or America.

Although some upgrading studies exist these have mostly relied on qualitative measures and arbitrary grading scales to determine feasibility of building upgrading (e.g. Caccavelli and Gugerli 2002). Some studies also report economic analysis (e.g. Kumbaroglu and Madlener 2012). Almost all studies use a particular type of building as a case study and some variation in the input data model is manually generated to be representative of a particular stock subset. A large number of optimisation scenarios are possible and different optimisation techniques used to determine a feasible set (e.g. Kaklauskas et al., 2005). Findings mostly focus on either energy or economics. Analysis of relevant domestic tools was conducted by Mills (2004) who evaluated 65 tools and found lack of content required for decision-making. Additionally he noted significant redundancy and fragmentation as well as inconsistencies.

One method for adequately assessing the energy implications of retrofit operations is to conduct pre and post retrofit conditions monitoring of a representative sample and extrapolate beneficial outcomes to the entire housing stock. Findings can then be encapsulated within a bespoke tool and training provided to interested parties. This is described in the remainder of this paper.

### **Data collection using pervasive sensing**

65,000 dwellings in Glasgow have a poor to moderate National Home Energy Rating (NHER) (SHSC, 2012). Installing or upgrading insulation is one of the most effective ways to improve the energy efficiency of these buildings and the Energy Saving Trust estimates that an uninsulated dwelling loses a third of all heat through the walls. As a result, insulation can significantly increase thermal comfort and reduce heating bills.

Consequently a low cost method for the assessment of upgrades applied in the urban context was developed. It comprised the monitoring of a representative sample of 65 dwellings and insulation upgrade approaches, with computer modelling studies used to undertake assessments and extrapolate beneficial outcomes to the entire housing stock. The project set out to test four hypotheses relating to demonstrating the usefulness of good quality building upgrading. It was hypothesised that:

- sensors can be deployed in dwellings to enable a low cost and rapid confirmation (or otherwise) of the efficacy of insulation upgrades;

- occupants will accept the imposition of short-term indoor monitoring in return for useful feedback or remedial action where appropriate;
- future upgrades will benefit from mandatory monitoring applied to a representative sample of the estate being targeted; and
- the quality assurance of upgrade programmes can be supported by the existence of openly available evidential case studies.

These hypotheses have been examined in relation to dwelling upgrades being undertaken within eight districts in the city of Glasgow. The buildings monitored had a range of characteristic types and age bands typical to the city. In brief, the properties consist of:

- ground and top floor flats of 4-in-block properties;
- ground, mid and top floor flats in tenement and high rise apartments blocks and two storey maisonettes; and
- semi-detached single and two storey dwellings.

Upgrade measures consisted of application or improvement of one or more of internal or external wall insulation, underfloor and/or loft insulation and double-glazing. The dwellings were mostly occupied by between one and three adults some of which were in full time occupation. A few dwellings had children. Figure 1 shows typical dwellings.



Figure 1 Typical uninsulated property (left) and externally insulated property (right)

Monitoring of these dwellings included a pre-upgrade and a post-upgrade period. It was made sure that monitoring was conducted within the heating season as far as possible. The upgrades involved real world complexities stemming from occupant behaviour, changing weather conditions, construction scheduling, privacy impacts etc. therefore it was necessary to adopt an approach that could normalise for such factors. The following steps were taken to ensure confidence in the measurements:

- initial deployment was at least one week prior to upgrade works commencing
- sensors were placed away from windows and doors and out of reach of children
- occupants were advised not to move the sensors
- occupants were advised not to disconnect power to the loggers
- sensors were removed after second post-upgrade meter reading

In the case of insulation upgrades undertaken in the summertime, it was necessary to arrange for the pre- and post-upgrade monitoring to take place during consecutive heating seasons. Where this was not possible post-upgrade monitoring still provided a valuable indication of the internal environmental conditions after insulation deployment and highlighted concerns where temperature and relative humidity measurements exceeded recommendations. Other factors affecting post-upgrade energy saving calculation include:

- occupants taking a holiday so that the property is unoccupied for several days; and
- periods of high outdoor temperature (normally during the Spring/Autumn) causing the heating system to switch off and internal temperatures to rise above normal controlled levels.

A weather station was installed at each site. The station transmits air temperature and humidity, and is located in a secure location sheltered from solar radiation. The real-time basis of the insulation upgrading programme meant that each upgrade began almost immediately after the occupant has agreed to take part, so before-and-after monitoring was not always practicable. Where possible, before-and-after and side-by-side comparisons of upgrades were undertaken.



Figure 2 A typical monitoring installation

The equipment required to monitor indoor conditions comprises two combined temperature and humidity sensors located within each dwelling, each with a built-in low power radio transmitter. Figure 2 shows a typical installation of sensors. A single radio receiver associated with each group of dwellings collects data from each sensor at 5-minute frequency. The receiver records the readings and these are then downloaded periodically. Sensors within properties have to be positioned in such a manner as to obtain a reasonable measure of temperature and humidity, but at the same time be unobtrusive to occupants and not susceptible to interference. To provide consistent measurements of room conditions, it was also necessary to ensure that each sensor is not moved significantly away from its location during the monitoring period, particularly if a property is insulated during that period. Small adjustments may be made to sensor readings to simulate a centre-of-room positioning. In each dwelling, one sensor was installed in a living or bedroom area, and a second sensor in a kitchen or bathroom depending on where high humidity levels are likely to be experienced. Figure 3 shows typical sensor/transmitter and receiver equipment.



Figure 3 Typical sensor (right) and receiver

The sensor is capable of wireless communication with the receiver. The receiver that has some local memory doubles up as logger. The receiver also has a router and server built into it. Details can be found in Clarke and Hand (2015). In addition to condition monitoring utility meters were also read for the pre- and post-upgrade period.

## Results

Figure 4 shows temperature recordings that are obtained from monitoring of two dwellings over a period of a few days. The most dominant variation that can be observed usually follows the daily fluctuations of outside temperature ( $T_{ext}$ ). There is a wide variation in temperatures possibly due to occupant behaviour despite these being similar properties. The property SH4, with occasional daily peaks in the kitchen most likely due to cooking activity, exhibits a distinctly higher temperature than the other does. Various occupant and heating system behaviours may be deduced by inspection of the graphs – some examples are highlighted on the figure.

Internal humidity levels are strongly related to internal temperature. A rise in temperature will lead to a fall in RH, without any moisture addition or removal. Considerable variation exists between properties, although most fall in the range 40-60% RH. Consistently high values of RH should be investigated, particularly after the property has been insulated, to ensure no internal condensation problems are occurring, particularly at cold bridges.

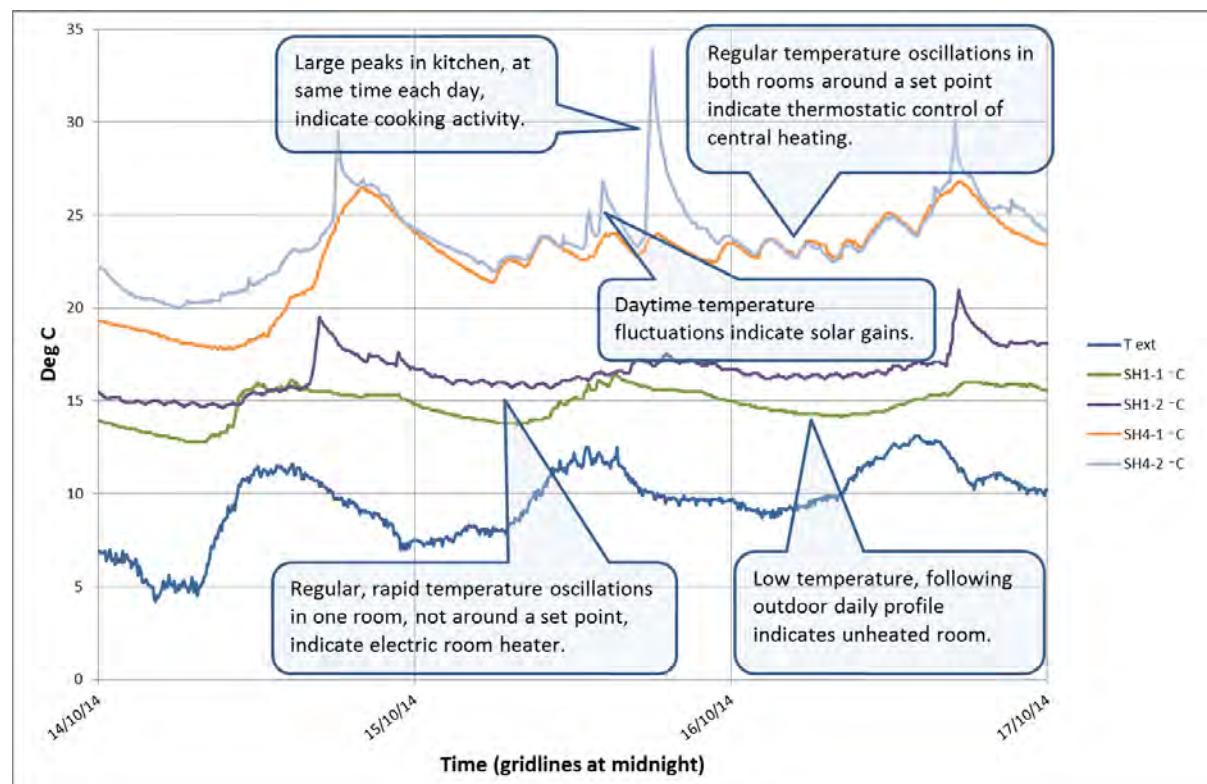


Figure 4 Typical temperature recording and observations for two properties SH1 and SH2 (for both indoor sensors 1 and 2)

The acceptable range of temperature is what the “average” occupant would report as being comfortable; in this case, the range is 19°C to 23°C (CIBSE, 2006). The same document also defines an acceptable RH range from 40% to 70% RH. Note is made of any notable fluctuations out with these limits, and their duration. Generally, short duration fluctuations do not cause problems. Longer duration fluctuations may need to be investigated.

One dwelling was found to exhibit variations in RH of up to 80%. It was known that the resident is disabled, and this might have a bearing on the data pertaining to this property. This property had been insulated, so an investigation might be called for here to ensure no internal condensation problems are occurring, particularly at thermal bridges. An example of a thermal bridge is shown in Figure 5 where insulation has been omitted around a gas meter and pipework.

Another property exhibited severe mould growth problems on the inside surface of the outer walls (Figure 6). Closer inspection revealed that mould had formed on the double glazed window seal, suggesting that condensation had been forming on the inner pane of the window. This suggests that the problem is condensation, not a building fault. The recorded data showed particularly high humidity levels regularly exceeding 80% RH. The dwelling will benefit from additional ventilation (opening windows perhaps) when cooking, bathing or drying clothes indoors. While the insulation applied to this property reduced the condensation problem on the walls, further inspection would be required to detect if any residual cold bridges had been created during the insulation process, as this could become a problematic source of hidden dampness.



Figure 5 Thermal bridge due to non-insulated section around a gas pipe and meter box and meter box



Figure 6 Occurrence of a severe mould growth problem on inside of windowsill

### **Environmental conditions analysis from monitored and modelled information**

Upgrades were assessed in terms of energy and indoor environment quality. The energy consumption measured during the monitored periods was used to estimate the annual energy saving because of applying the upgrades. This saving was compared with a benchmark saving estimate calculated using calibrated computer modelling after compensating for changes in external conditions during the whole process.

High humidity and temperature levels were diagnosed as shown in Table 1.

The diagnoses will be tempered by correlating the observations with maximum occupancy levels and average outside temperature and humidity conditions. For example, a high internal humidity level in winter when external humidity is high is of lesser concern than when external humidity is low. High internal humidity peaks are of less concern if occupancy is high. A priority rating system was proposed that, as a demonstration of a potential energy-related service, could be generated through automated data analysis via an intelligent agent.

Table 1 Environmental data.

	Temperature	Humidity	Energy use	Potential diagnosis
1	High for extended periods	Any	High	Poor temperature control / wasted energy.
2	Low for extended periods	Any	Low	Fuel poverty alert.
3	High peaks	High peaks	Any	Poor ventilation during cooking / bathing
4	Medium	High for extended periods	Any	Poor ventilation at all times / internal clothes drying.
5	Low	High	Any	As 3 with high internal condensation risk
6	Wide range	Low / medium	High	Excessive ventilation (maybe window opening).
7	Low / medium	Any	High	Check for thermal bridges.

### Front end graphical user interface

A Post Operations Evaluation Tool (POET) was developed to provide a method for the automatic confirmation of the quality of an insulation upgrade. This provides an evidence-based quality assurance test of the upgrade that supports project sign-off. The tool requires basic information on the property such as its archetype, construction, occupancy, floor area, upgrade type, and a suitable weather station location to be used in the analysis. It utilises meter readings and monitored indoor conditions data in order to assess the insulation upgrade. Feedback is provided based on analyses relating to energy performance and post-upgrade internal environmental conditions.

Based upon the property details a predicted energy performance benchmark is selected from a database of ideal performance benchmarks as determined from dynamic computer simulation. The pre- and post-upgrade energy consumption of the dwelling, determined from meter readings is normalised using the relevant outdoor temperature data from the selected weather station. This determines the savings achieved by the property's upgrade. The benchmark saving is compared to the actual saving achieved to determine how close the property came to achieving its theoretical value. This information used alongside the property energy survey data allows an assessor to determine if the upgrade has achieved its goal.

Textual feedback from an underlying environmental conditions assessment algorithm is also provided. This algorithm assesses the post-upgrade indoor temperature and humidity profiles as monitored in order to determine if these are within acceptable ranges. This allows the assessor to identify acceptable indoor environmental performance post-upgrade and isolate possible causal factors where this performance is deemed unacceptable. Details on the energy and environmental assessment algorithms are available from within the interface.

The assessment section of the tool launches the evaluation of the algorithms, and generates a compliance report. The report provides a summary of the dwelling's performance along with any recommendations for follow-up action.

In order to test the operation and application of the tool, it was deployed within the GCC's Housing Strategy Group and subjected to user trial using sample data as collected within the project and representing different possible upgrade outcomes (acceptable,

unacceptable and ambiguous). Training in the use of the tool allowed the assessors to easily assess quality of retrofits and generate compliance reports.

## Conclusions

It was shown that a pervasive monitoring approach is useful in appraising the quality of retrofit for domestic buildings. Results from pre- and post- retrofit monitoring of internal and external conditions and energy use were used to ascertain whether upgrades had been applied to an acceptable level or otherwise.

Patterns of temperature and humidity fluctuations and their correlation with external conditions and information about building use was used to determine additional features of the dwellings and their use. Such analyses can show problematic environmental control, fuel poverty, poor or excessive ventilation, risk of condensation and thermal bridging.

## Acknowledgement

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## References

- Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C., Palmer, J., Sinden, G., Lane, K., Layberry, R., Wright, A., Newborough, M., Natarajan, S., Peacock, A. 2005. 40% House, Environmental Change Institute, University of Oxford, Oxford, UK.
- Caccavelli, D. and Gugerli, H. 2002. TOBUS – a European diagnosis and decision-making tool for office building upgrading, Energy and Buildings 34 (2002) 113-119.
- CIBSE 2006. Chartered Institute of Building Service Engineers (CIBSE), CIBSE Guide A: Environmental Design, 2006, ISBN-13 9781903287668
- Clarke, J. Hand, J. 2015. An overview of the EnTrak/ BuildAX eService delivery platform. Occasional paper. Accessed 6-Feb-17 [http://www.esru.strath.ac.uk/Documents/15/eservices\\_230115.pdf](http://www.esru.strath.ac.uk/Documents/15/eservices_230115.pdf)
- Clarke, J., Johnston C., Kelly, N., Strachan, P., Tuohy, P. 2008. The role of built environment energy efficiency in a sustainable UK energy economy, Energy Policy 36 (2008).
- Ernst & Young. 2010. Business opportunities in a low carbon economy, Final report, Industry and Investment. New South Wales, Australia.
- Hong, H., Oreszczyn, T., Ridley, I., the warm front Study Group. 2006. The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings, Energy and Buildings 38 (2006) 1171-1181.
- Kaklauskas, A., Zavadskas, E., Raslanas S. 2005. Multivariant design and multiple criteria analysis of building refurbishments, Energy and Buildings 37 (2005) 361-372.
- Kumbaroglu, G., Madlener, R. 2012. Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy and Buildings 49 (2012) 327-334.
- Mills, E. 2004. Inter-comparison of North American residential energy analysis tools, Energy and Buildings 36 (2004) 865-880.
- SHSC 2012. Scottish House Conditions Survey, 2012, ISBN 9781784121549.
- The Rockefeller Foundation and Deutsche Bank Group, DB Climate Change Advisors. 2012. United States Building Energy Efficiency Retrofits. Market Sizing and financing Models.
- URL 1. Accessed 8-Oct-16. <http://www.bmvbs.de/en/Building/Climate-change-and-energy-effi,-2826/Programme-to-reduce-CO2-emissi.htm>



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A New Parametric Framework: Developing Design Options in Real Time

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**Abstract:** Current architectural design practice is limited in its consideration and understanding of life-cycle energy flows which comprise multiple phases, from material resource extraction, construction, building occupation within the built environment, and after demolition. Furthermore, bioclimatic environmental flows interact with the buildings, particularly at the building envelope, making it a rich interface for shaping energy flows towards buildings that are energy self-sufficient with clean on-site energy resources. The buildings we inhabit directly affect the greater built environment which is an inherent part of local ecosystems which compose part of larger ecologies at global scales, ultimately affecting the overall biosphere. As a result, the buildings we construct, directly and indirectly, affect our economies, the health, and well-being of our societies and our natural environments. This paper explores the development of a computational framework that provides architects and designers direct feedback on design performance at the schematic design stage. This allows designers to visualize, understand and evaluate their design choices in terms of their environmental implications and ecological efficacy. This framework for design analysis offers a more comprehensive ecological analysis than existing sustainability assessment tools, by considering the entire temporal building process. Working with Rhino/Grasshopper as a widely-used software platform allows for interactive feedback to architectural designers as they develop design options in real time. This paper will use a case study, assessing a solar decathlon house, demonstrating the qualitative and quantitative environmental impacts of the building design.

**Keywords:** multi-disciplinary, parametric modelling, building performance analysis, tool development.

### Introduction

Current architectural design practice is limited in its consideration and understanding of life-cycle energy flows, which comprise multiple phases, from material resource extraction, construction, to building occupation within the built environment (Keena, et al., 2016). Furthermore, bioclimatic environmental flows interact with the buildings, particularly at the building envelope, making it a rich interface (Schumacher, 2012) for shaping energy flows towards buildings that are energy self-sufficient with clean on-site energy resources. The process of constructing and operating buildings often leads to environmental outcomes that are not nourishing<sup>1</sup> to either physical or social ecosystems (Graham, 2009). Due to the siloed structure of the building industry and the endemic lack of environmental awareness among building professionals and the industry as whole, the process of delivering built environment systems has played a major role in the decline of Earth's ecological health (Hancock, 2011). Our built environments (Koren & Butler, 2006) are in fact built ecologies (Dyson, 2011) (Winn,

<sup>1</sup> According to the U.S. Energy Information Administration (EIA), the building sector consumes (47.6%) of all energy produced in the US, and 74.9% of all the electricity produced is used just to operate buildings. Therefore, the building sector is responsible for 44.6% of US CO<sub>2</sub> emissions in 2010.

et al., 2012) in that they are part of larger interdependent global ecosystems and they, directly and indirectly, have significant effects on our populations' health and well-being, our economies, and on global biodiversity (Raupach, et al., 2007) (Odum, 2007).

The innovation of built ecosystems that can sustain and be sustained by resilient, biodiverse, living systems is urgently required. This research aims to develop an approach towards protecting the life-supporting goods and services of ecosystems (Bakshi, 2002; Keena, et al., 2016) and providing the basis for sustained life opportunity on Earth by offering accessible information and feedback during the design decision-making process. This research is supporting the development of a novel visualization framework that characterizes both the characterization of thermodynamic as well as the ecological performance of the building systems (Aly Etman, et al., 2016), and the possibility to reshape the role of the building professional (architect) from one who directs the implementation of a structure, to one who designs and implements a system of relationships between ecosystems and human systems within the built environment. The eco-systemic integration across systems has become extremely difficult to achieve under the current paradigm, as the architecture, engineering, and construction (AEC) industry invested enormous resources towards the development of a building design and implementation process that separates consultants on the same design team, in order to clarify spheres of responsibility and to defend against liabilities.

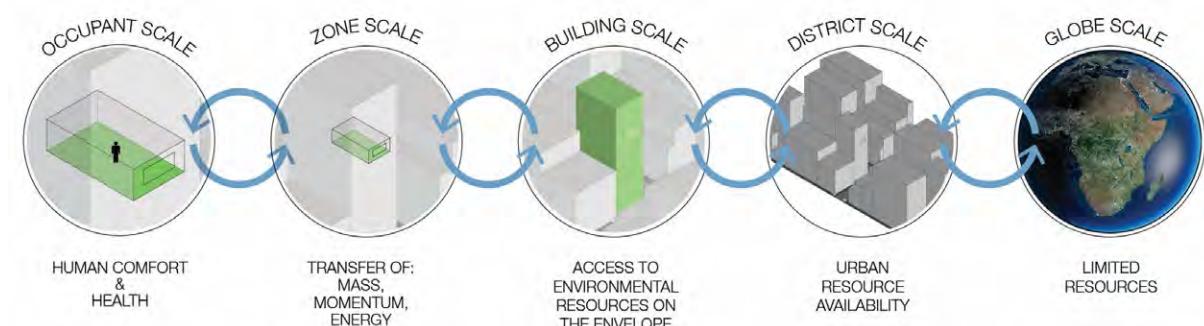


Figure 1 Our built environment is part of a larger global ecosystem affecting our global economies, our health and well-being, and our natural environment, i.e. Built Ecologies.

By contributing to explicate built environment systems, this research intends to help facilitate a transition from the mechanical paradigm (Kuhn, 1962) towards an ecological paradigm (Bateson, 1972) (Fernández-Galiano, 2000). This framework will provide architects facts and knowledge about the environmental influences on their design decisions and the interdependencies between the building next generation systems and nature, and will offer new approaches on how to achieve comfort with nature (Aly Etman, et al., 2016).

## Background

The building process is slow, expensive, and risky. Data is increasingly fast, cheap, easily accessible and seems to offer the hope of providing new levels of certainty on complex problems. A widespread paradigm shift has occurred in design thinking whereby performance requirements have far greater influence on the decision-making process, however, access to reliable and extensive data during critical phases in the decision making has been difficult to achieve. In architecture, generative computational frameworks can support systems design exploration and expand the solution space for a multitude of formal iterations while satisfying

and optimizing performance requirements (Winn, 2014). This paradigm also promises the designer the power to work through generative systems processes through parametric computation. This approach is identified as ‘Generative Performative Design’ whereby both form and performance requirements drive the generation process (Fasoulaki, 2008). The use of building performance simulation tools by design professionals has become a fundamental way to support design decisions for energy efficient buildings. Yet there are now so many environmental claims, simulation tools, and metrics that architects need a context within which to evaluate them in order to advance the conceptual design phase of high-performance buildings. Despite the plethora of environmental analysis tools, contemporary approaches to design are still often based on economic determinations of value, in which environmental contributions and renewable resources are almost entirely discounted or even considered free. In the context of these considerable challenges, a novel comprehensive and synthetic workflow environment is proposed that AEC professionals can use from the earliest and most impactful stages of design onwards to generate initial decisions that are environmentally responsive.

Recent studies have discussed the potential benefits of better integrating environmental analysis and building simulation into the design process (Weytjens, et al., 2012). Weytjens has demonstrated that the interface and input method should be intuitive; thus proprietary modeling rules must be avoided. In addition, energy analysis tools should harmonize with architects’ typical working methods to add value to the architectural design process. Architects used to be restricted by what they could calculate. With new computational tools, architectural practices can model, understand and simulate the flows. Currently, the development of such tools is booming. However, since the built environment with its complex matrix and fluxes is a giant information-rich interface, the resulting outcomes have become overwhelming. These databases present numerous challenges for visualization, interaction, and participation for the designer and the public. For example, a significant amount of effort and time is often spent organizing the data before extracting any analysis to infer new knowledge from them. This research proposes a framework to allow architects to handle, visualize and interact with the spatiality and complexity of current and new buildings.

### **Previous Efforts**

In order to investigate the impact of design decisions properly, we should examine the temporal energy flows at the pre-building, building, and post-building phases. The existing tools and software available were developed with one aspect of the problem in mind, so they do not fully support the integrated design process. However, the resulted calculations are still challenging and tedious, and best practices for analysis are not well defined or propagated. Current tools, such as Energy Plus, Radiance, Sefaira and so on, can help predict and project the impact of our proposed (design) building, but they only focus on one phase: either the material lifecycle or the operational energy. This disconnection is forcing the investigator to use multiple tools, which increases the effort needed and invites errors. Eco-centric views and techniques are crucial for appreciating the contribution of ecosystems to all human activities and meeting the challenges of sustainable development.

## Proposed Solution: Integration Of Design And Analysis In A Parametric Environment

This paper is built on research that uses disciplinary-specific methodologies for data collection and analysis but employs a mixed method feedback loop for collaborative design and integrated system evaluation.

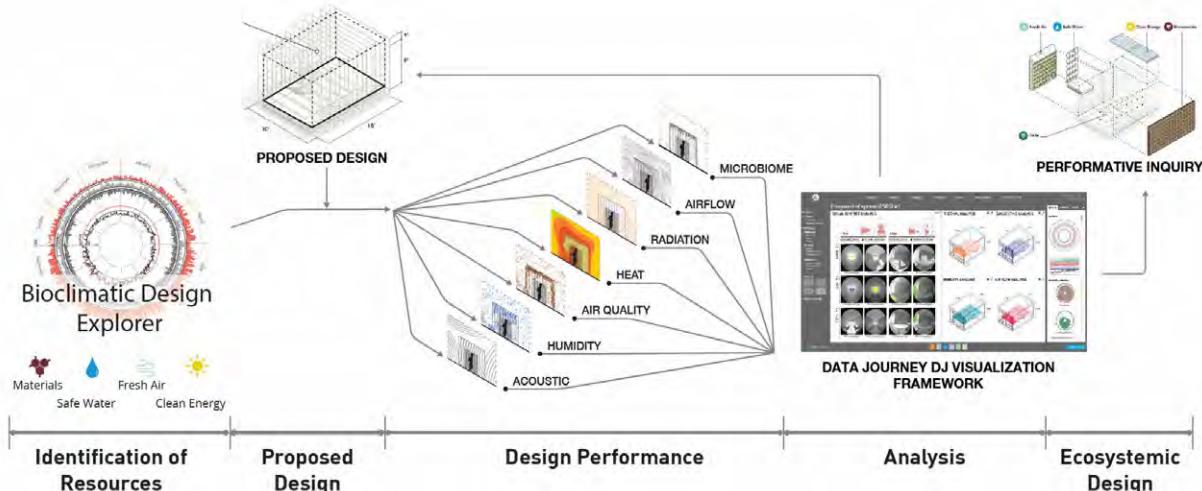


Figure 2 Proposed design and evaluation framework. Feedback loops between all three scales highlight the importance of inter-scalar design strategies.

Parametric modeling tools have recently introduced a new modeling and design approach to the architectural community. Parametric modeling, by nature, is based on data; connections and changes between different levels of evidence (data) are instantaneous. This method provides multiple benefits for integrating design and analysis. The ability to visualize environmental analysis data within the design platform allows designers to make clear connections between data analysis and design. Within the parametric platform of Grasshopper3D, the visual programming language and environment for Rhinoceros3D, building details, which are generated from the base geometry, remain as layers of the base data. When optimization of the base geometry occurs, which is appropriate for environmental analysis modeling, the parametrically-linked details automatically update. A single model is used for both the design model and the analysis model, facilitating a smoother, more integrative and efficient workflow. The proposed framework, shown in Figure 2, is intended to leverage the popularity and ease of use of existing plugins that allow interfacing validated software, i.e. Ladybug and Honeybee, by extending their capabilities so they can analyze the projected impacts of the proposed design on the environment.

### Case Study

To test this framework, a case study, based on the guidelines of the solar decathlon houses (U.S. Department of Energy, 2002), was proposed as a foundation for designing a net-positive, solar powered residence and adapted that model to fulfill the research objectives better. This house was designed to be placed in Paris, France and followed the design limitations of a solar decathlon house. A house that wins the solar decathlon could easily be (and has been in the past) a black box of solar panels, but this research calls for a higher standard of performance relative to human health and comfort, ecological health, and systems intelligence.

### **Step1: Identification of resources**

The first step, the identification of the available resources, within the proposed framework required the development of a visualization strategy which builds upon existing radial graphical layouts to contribute customized techniques for exploring patterns in multivariate weather datasets. Shown in Figure 3, the 'Climate Clock' design tool accompanied by a series of smaller 'Fob Clock' visualizations, present a multi-faceted interactive visual representation of multiple aspects of climate synthetically. The 'Fob Clocks' are designed and implemented to allow the user to explore and investigate the various potential bioclimatic design approaches based on specific weather data imported as Typical Meteorological Year (TMY) datasets. The Climate Clock represents the annual weather data both cyclically and linearly, via a zoom function which allows the user to explore a specific range of the cyclically represented data in a linear fashion. The Fob Clocks, a group of radial area charts, and a Psychrometric chart supplement the visualization with bioclimatic analyses that direct the user to identify the existing resources.

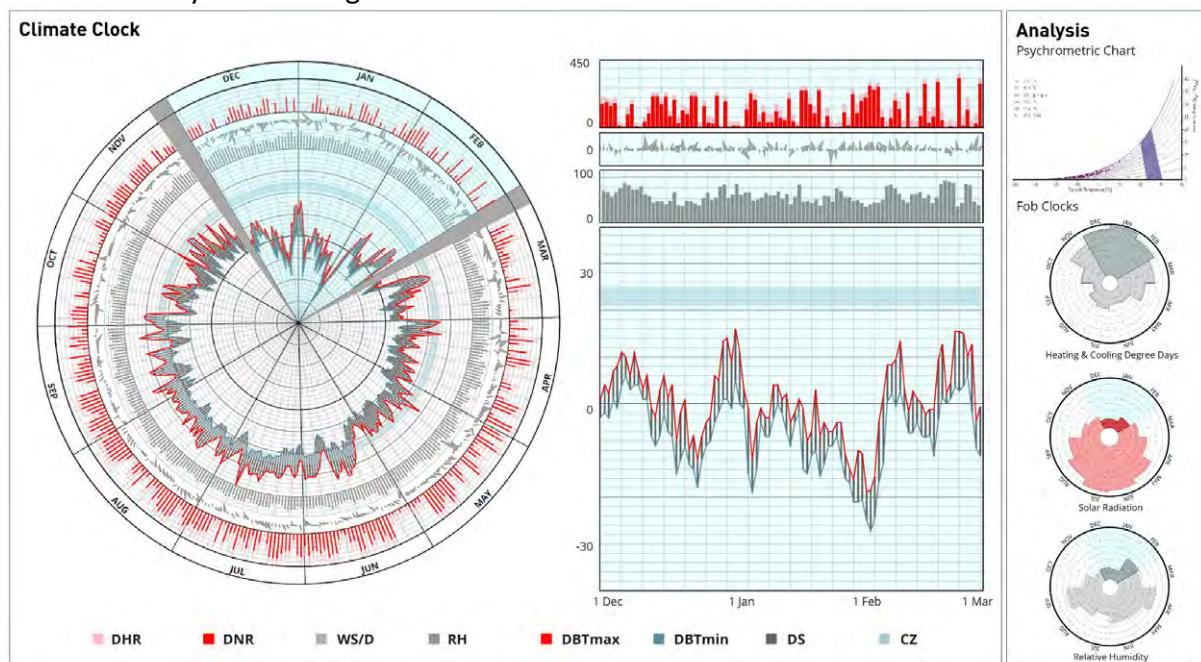


Figure 3 The Climate Clock tool.

### **Step 2: Developing a design:**

In order to investigate the proposed framework, a schematic design of a solar decathlon house for an artist in residence has been selected, shown in Figure 4, which created some additional design criteria. For example, it brings the house into an interesting category somewhere between residential and commercial. There is a greater need for calibrated lighting conditions, additional plug loads, and a re-invention of the typical occupancy schedule.

It utilizes layered active and passive systems to create a data collecting, energetically net-positive house that is thermodynamically and visually comfortable while fostering productive, creative, healthy occupants. The design objective was established to achieve a net-positive, solar powered residence. The design ecosystem was designed to harvest and metabolizes solar energy, to thermo-regulate its internal temperature in healthy and efficient ways, to utilize biomechanical lungs to produce fresh air from within, to manage energy flows

between the environment and occupants intelligently, and to contribute to the health of the ecology at large.

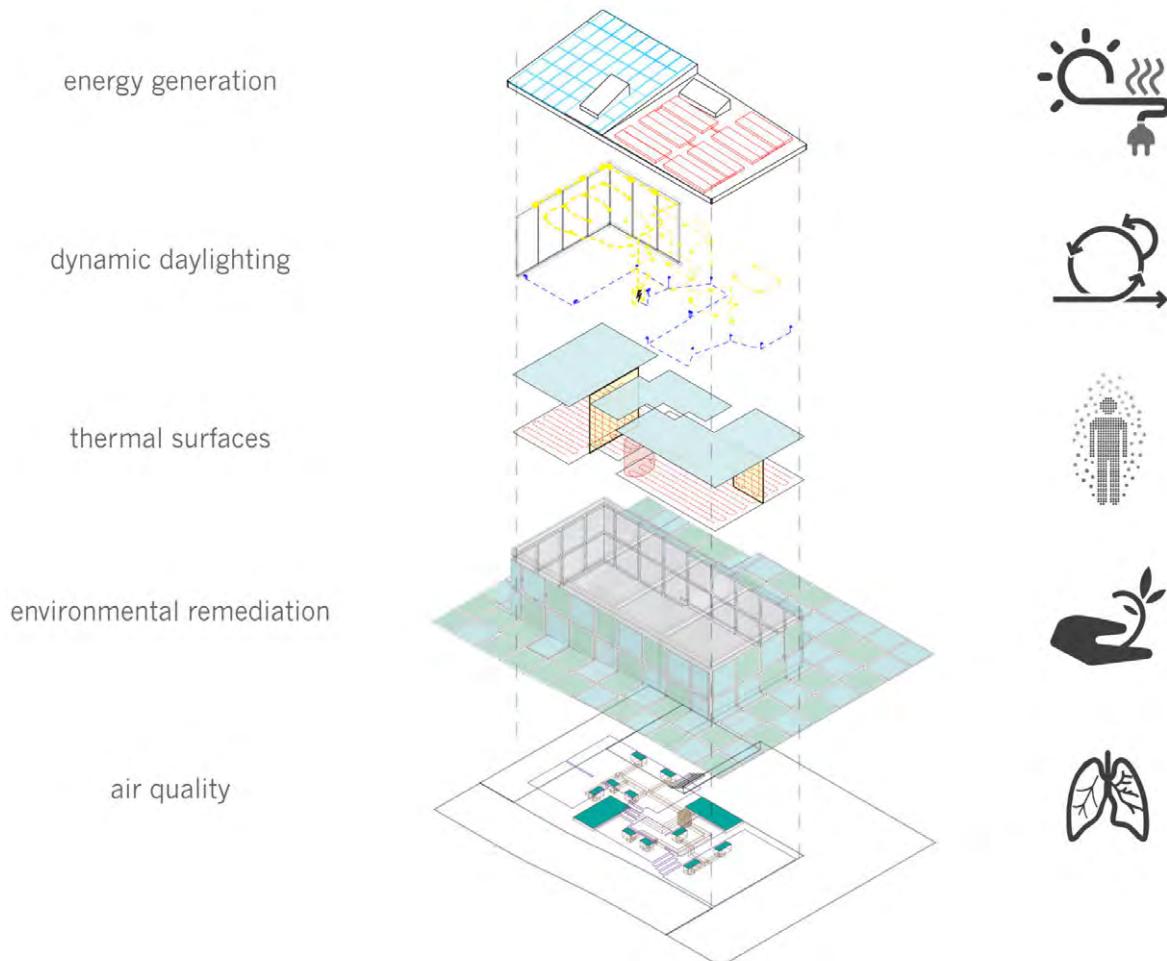


Figure 4: Diagram of the proposed design and the selected mechanical systems.

### **Step 3: Design performance:**

The next steps are to investigate the resources (climatic), selected systems performance, and their interdependency. By analyzing a matrix of system behaviors, the framework will help the user to understand which systems are most effective for the selected climate. In this case, we studied how various behaviors affect the relationships between climate inputs, building demand, resources, and performance criteria. Moreover, then proceeded to select and develop nested systems that meet our energetic performance criteria as well as human serviceability, comfort, and control criteria. The performance of the selected systems is simulated using Energyplus v.8.4 through grasshopper plugins (i.e. Ladybug, Honeybee) for the proposed design. The simulation outputs in (Figure 5) show the parameters of investigation alongside the criteria of analysis.

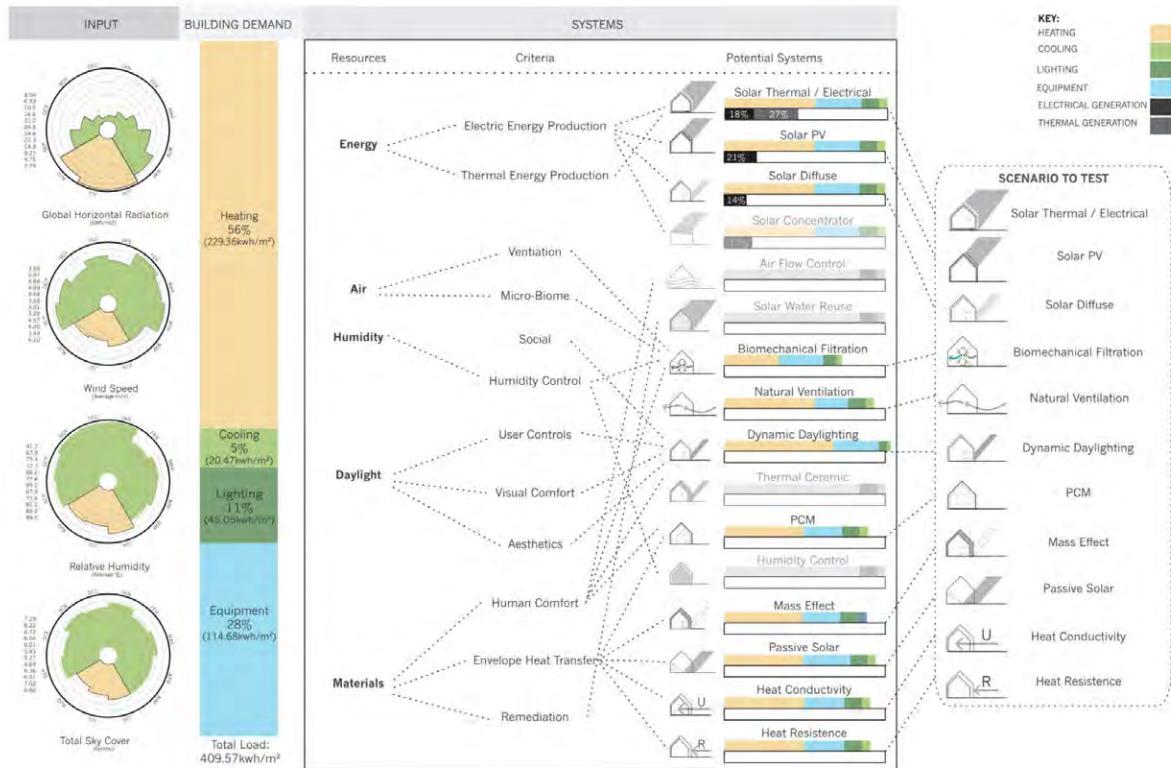


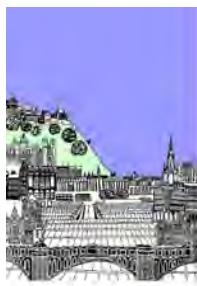
Figure 5: The analysis of systems integration of the different cases in ( $\text{kWh}/\text{m}^2$ )

## Conclusion and Discussion

Current building research and development frameworks view the architect as the one who directs the implementation of a structure. However, with increasing access to data and modeling attributes, the architect within the proposed research framework has the agency and opportunity to foster a system of relationships between ecosystems and human systems within the built environment under critical broadened performance criteria. The aim of the research is to develop a parametric framework that can be flexibly scaled for testing multiple building typologies, current and next generation systems. The framework will empower the designer to design climatically responsive buildings that can not only achieve thermal comfort for occupants, but that can also make significant reductions in energy consumption in heating and cooling, and the spread of air pollution. Such a tool would help architects develop built ecologies that will allow for buildings to function as ecosystems working with their microclimates. The parametric tools should enable designers to overcome the previous workflow limitations. Implementing building performance simulation tools in the designer's environment should encourage an environmentally-conscious design workflow. Such tools will create an awareness of the environmental impact of our buildings and design processes on our environment. In this framework, architects and designers can compare different weather conditions for several contexts, various design options, material types, and numerous building systems. Different designs can be compared and analyzed parametrically to show the entire built environment process, which at the early phases of design (while there is not the budget nor time to conduct extensive investigations) holds great potential.

## References

- Aly Etman, M. et al., 2016. *New Parametric Framework Motivating Environmentally Conscious Design*. Los Angeles, In Proceedings of the PLEA 2016.
- Aly Etman, M. et al., 2016. *Interactive Visualization for Interdisciplinary Research*. Seattle, Electronic Imaging, pp. 1-7.
- Bakshi, B., 2002. A thermodynamic framework for ecologically conscious process systems engineering. *Comput. Chem. Eng.* 26, p. 269–282.
- Bateson, G., 1972. *Steps to an Ecology of Mind*. Toronto: Chandler Publishing Company.
- DOB, 2014. *Building Code Title 27 Subchapter 12 - NYC.gov*. [Online] Available at: [http://www.nyc.gov/html/dob/downloads/bldgs\\_code/bc27s12.pdf](http://www.nyc.gov/html/dob/downloads/bldgs_code/bc27s12.pdf) [Accessed 15 February 2016].
- Dyson, A. T. N. a. J. V., 2011. Characterizing the Problem: Bioenergetic Information Modeling.. In: *BIM in Academia*. New Haven, CT: Yale School of Architecture, pp. 28-41.
- Fasoulaki, E., 2008. *Integrated design: A generative multi-performative design approach*. Boston: Doctoral dissertation, Massachusetts Institute of Technology.
- Fernández-Galiano, L., 2000. *Fire and memory: On architecture and energy*. Cambridge: Mit Press.
- Graham, P., 2009. *Building ecology: First principles for a sustainable built environment*. ed. : John Wiley & Sons.
- Hancock, T., 2011. It's the environment, stupid! Declining ecosystem health is THE threat to health in the 21st century. *Health Promotion International*, , 26(suppl 2), pp. ii168-ii172.
- Keena, N. et al., 2016. *Visualization Framework to Evaluate the Emergy of Built Ecologies*. Gainesville, Florida, In Proceedings of the 9th biennial emergy conference. Center for Environmental Policy, University of Florida.
- Keena, N., Aly Etman, M., Rempel, A. & Dyson, A., 2016. *Designing Built Ecologies: Investigating the Potential of Emergy Analysis to inform the decision making process within Architectural Systems Design*. Los Angeles, In Proceedings of the PLEA 2016.
- Koren, H. S. & Butler, C. D., 2006. The interconnection between the built environment ecology and health. In: *Environmental Security and Environmental Management: The Role of Risk Assessment*. s.l.:Springer Netherlands, pp. 109-125.
- Kuhn, T. S., 1962. *The structure of scientific revolutions*. : University of Chicago press.
- Odum, H. T., 2007. *Environment, Power and Society for the Twenty-First Century*. New York: Columbia University Press.
- Raupach, M. et al., 2007. Global and regional drivers of accelerating CO<sub>2</sub> emissions. *Proceedings from the National Academy of Sciences*, Volume 104, pp. 10288-10293.
- Schumacher, P., 2012. Parametric semiology—The design of information rich environments. In: *Architecture in formations—On the nature of information in digital architecture*. New York, NY: Routledge, Taylor and Francis.
- U.S. Department of Energy, 2002. *Solar Decathlon*. [Online] Available at: <https://www.solardecathlon.gov> [Accessed 07 June 2017].
- Weytjens, L., Macris, V. & Verbeeck, G., 2012. *User Preferences for a Simple Energy Design Tool: Capturing information through focus groups with architects*. Lima, Peru, PLEA.
- Winn, K. R., 2014. *Inter-scalar Multivariable Decision Making Framework for the Architectural Envelope*, Troy, NY: Diss. Rensselaer Polytechnic Institute.
- Winn, K., Vollen, J. & Dyson, A., 2012. *Re-Framing Architecture for Emerging Ecological and Computational Design Trends for the Built Ecology*. , ACADIA.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Experimental evaluation of the impact of window improvement in Social Housing and in real weather conditions REVen Laboratory in Madrid

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**Abstract:** This work is developed within the framework of the REVen Project “Energy retrofitting of social housing, using innovative window products with technical approval (DIT, ETA)”, whose overall objective is to generate window solutions for social housing retrofitting, considering technical and socioeconomic aspects. This is being done through different specific objectives developed mainly through simulations and experimental research. Experimental research has two main tasks: 1. Laboratory research: The REVen Laboratory will compare a low performance window with a higher quality window, which incorporate solar control devices in Madrid in real weather conditions, in Southern orientation. Heating and cooling loads, as well as other aspects of indoor environmental quality will be monitored; 2. Social Housing: In a dwelling in Madrid, consumption measurements have been taken for two years, windows have been replaced and measurements after the improvement are being performed. This paper addresses firstly, REVen Lab construction and monitoring and then a Social Housing monitoring before and after the improvement of the windows and results available will be those from winter 2017. Heating savings of 25% are measured.  
<http://proyectoreven.ietcc.csic.es>

**Keywords:** retrofitting, social housing, windows, experimental research, heating savings.

### Introduction

For existing buildings, the Energy Performance of Buildings Directive (European Commission, 2010) considers that the greater efficiency of the investment with respect to the improvements achieved is reached in major renovations of buildings, or the parts with the highest incidence on building energy consumption. In this sense, windows can be considered as elements of great incidence on consumption and therefore with great potential for associated energy saving. In Spain, (IDAE, 2011) between 25% and 30% of our heating needs are due to the heat losses that arise through windows.

In 2010, (Asociación de Ciencias Ambientales, 2012) 10% of homes in Spain did not have sufficient means to maintain a suitable temperature during the cold months, and/or spent a high percentage of their income to cover basic needs (heating, refrigeration, kitchen, lighting, hot water). In addition to being in a situation of thermal discomfort, there are serious health consequences that derive from living in a house with an inadequate temperature. Therefore, there is a percentage of users for whom action on the envelope of their dwelling is going to imply an improvement in their living conditions without necessarily seeing it reflected in their consumption, since they do not consume because they are in a situation of “Energy Poverty”.

The European Commission has already included the concept of energy poverty in its energy and consumer protection policies. Directives of the internal electricity and gas market oblige Member States to develop plans to address this issue (EC, 2009). Achieving optimum environmental quality will, therefore, be another objective set by the European Commission, as necessary as achieving an efficient use of energy.

Interior environmental quality refers to the state of health and comfort conditions of the different elements that condition our life. The main aspects to be considered in order to assure the internal environmental quality must satisfy the conditions of hydrothermal comfort, acoustic comfort, luminous comfort, physicochemical and microbiological contaminants in the air, and the electromagnetic environment (Bluyssen P.M.,2009) Out of all these aspects, the window intervenes in four of them: hydrothermal comfort, daylighting comfort, acoustic comfort, and air quality.

In addition to the complexity of its energy efficiency, it is necessary to treat windows as an essential element in relation to users and the indoor environmental quality. Modifying the essential elements of the window to improve its energy efficiency can be detrimental to some of its benefits. Determining the optimal window solution for each specific situation will involve an overall approach, analysing the compatibility between energy efficiency and IEQ.

REVen Projects aims to perform an overall analysis, this paper addresses the experimental research carried out so far: REVen Lab construction, monitoring and data analysis from the Social dwelling. Results available will be those from winter 2017.

## Methodology

The Project proposes a documentary/theoretical methodology that will be developed in parallel to an experimental one, in which measurement in real climatic conditions will be performed. In this experimental part there are two tasks: In REVen Laboratory a low performance window will be compared with a higher quality window, in real climatic conditions, in a south orientation. Heating, cooling, light and other electrical consumption will be measured and other aspects of indoor environmental quality will be monitored; in a social dwelling, consumption measurements have been taken during two years, the windows have been replaced; annual heating savings have been quantified, electrical consumption, CO<sub>2</sub>, relative humidity and air temperature are being monitored.



Figure 1. Experimental methodology: REVen Lab and Social Dwelling.

### **REVen Lab**

In glazing systems selection it is important to achieve a compromise solution, which will not be optimum in summer or winter conditions, but optimum during the annual cycle. Giving a

balanced response to all the energy flows that occur through this element and the requirements of interior comfort associated with it.

In order to characterize energy flows and internal environmental conditions, the REVen Laboratory (outdoor laboratory in real weather conditions) has been built, where different window solutions can be monitored, allowing to discretize variables, and to estimate its impact on both energy demand and environmental quality.

REVen Lab is built through a new industrialized construction system. It is a volume with two separate, quasi-adiabatic spaces facing south where the energy flow through the windows and the consumption associated with the different solutions will be monitored.

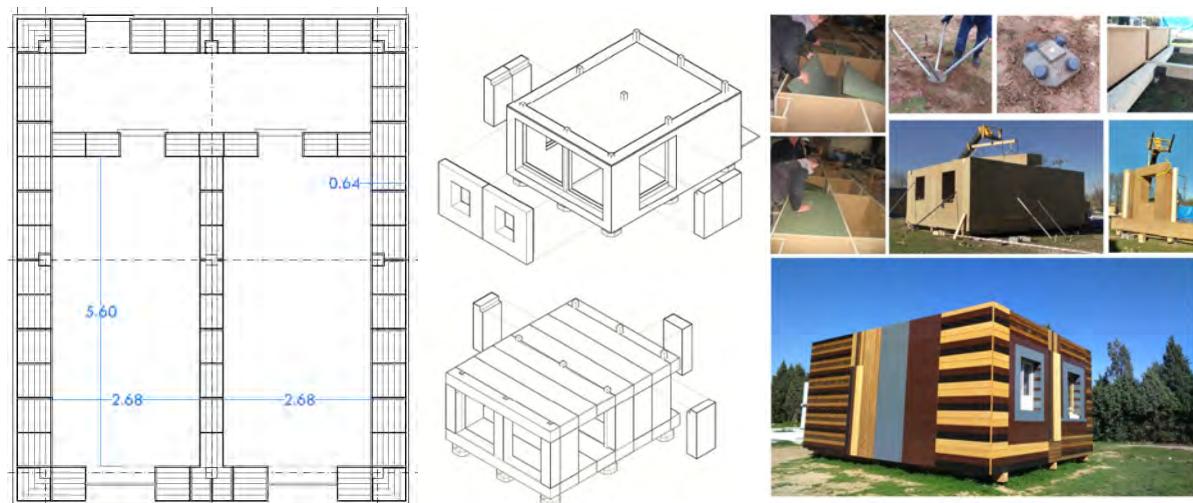


Figure 2. REVen Lab's Layout and Construction.

It has been built with wood, given the characteristics of the project; we want it to have the least possible environmental impact in addition to advancing knowledge of industrialized building construction with this material. It consists of an envelope of 60 cm of regenerated cotton insulation confined by wood panels, and laminated wood structure.

Dimensions of each room are 2.68m wide by 5.60m long; there is a service room at the north to enter to each space. The Lab can be disassembled and placed at another location. South, East and West façade modules can be removed to carry out future research on those areas.

#### ***Definitions of samples to be tested***

The reference window is a traditional window, aluminium (with thermal bridge), simple clear 4mm glazing and white awning, a common solution.

The optimised window incorporates an innovative wood frame, it has a greater surface of glass than a traditional wood framed window, the blade being even with the frame, the glazing incorporates argon, white louvres and integrates an innovative heat exchanger designed specifically for windows PremiVent.

The samples to be compared are 1.5m in height by 1.25m wide.

Table 1. Samples

	FRAME	GLASS	SOLAR DEVISE	AIR RENOVATION
Reference window:	Aluminium	4mm glazing	White awning	Open-Close window(traditional)
Optimised window:	Wood LighTEK 68	Planitherm XN F2 4(16 argon)4.	White louvres	PremiVent



Figure 4. Samples to be tested. On the left side Reference Window, on the right side Optimised Window.

### **Monitoring**

In order to evaluate the efficiency and operation of the selected system, monitoring of the experimental cells will be carried out.



Figure 5 Monitoring Layout

The evaluation of the efficiency of the systems comparing the HVAC consumption of the two rooms with the different window elements started in March 2017. In addition, other parameters related to user comfort, such as lighting levels, CO<sub>2</sub> levels, relative humidity, temperature and surface temperature of the windows are also being measured.

In each adiabatic space the following variables are being measured: 6 measurements of surface temperature by means of thermocouples, 1 relative humidity measure in the centre of the module, 1 air quality measure (CO<sub>2</sub>) in the centre of the module, 1 interior

temperature measure in the centre of the module and 3 daylighting measures. Independent measures of electrical consumption of: the heat pumps, lighting, solar protections, the heat exchanger and the window opening-closing motor.

### Social housing

REVen Project relies on previous research work REFAVIV Project (2013-2017), which focuses on opaque envelopes. They are complementary projects, as REVen is focused on windows. In REFAVIV Project, Social Houses were analysed, electrical and heating consumptions were monitored during two years. REVen Project continues working in one of those social houses.

Both Projects are conceived as “citizen science” where scientists, professionals and citizens collaborate. The selection of the houses is based on the housing stock characterization (Alonso et al., 2015), and due to the III National Plan of housing (1961-76), there is a great Social Housing building stock from this period which needs to be retrofitted, generally envelopes are poorly insulated.

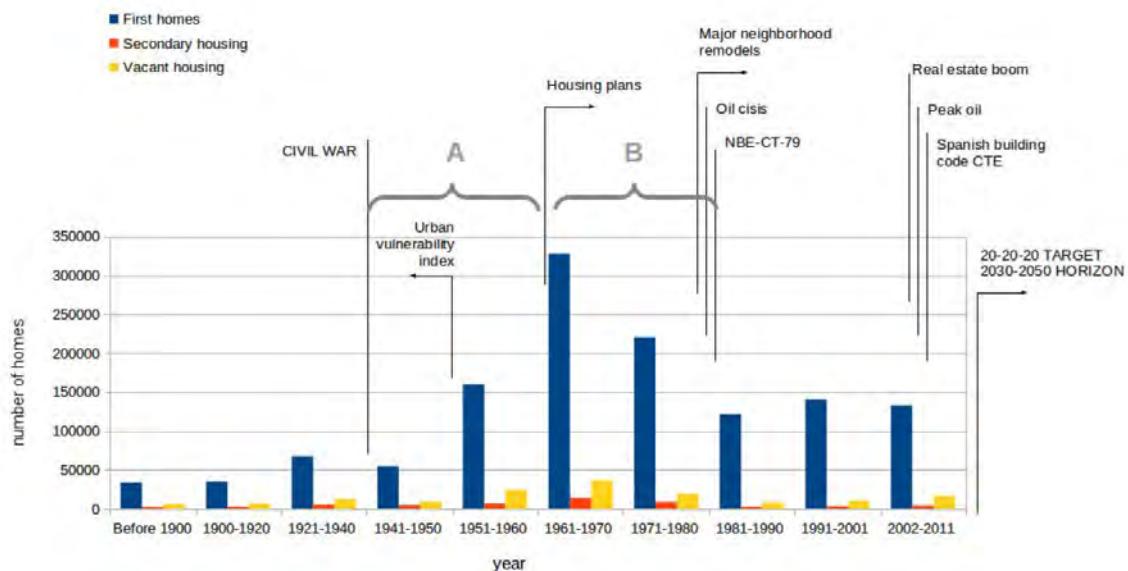


Figure 6: Number of dwellings built since 1900.

In figure 6, green indicates the number of main dwellings, and pink the number of secondary and empty dwellings according to the 2011 census of population and housing (INE, 2011). The dwelling in which this project is taking measurements is located in a multi-family block of five floors. Construction date is 1960 (the project data is from 1957) and the constructed area of the house is 71m<sup>2</sup>. It has a bedroom and living room oriented to SW and two bedrooms, kitchen and bathroom oriented to NE. The houses in this type of block are passages, which allow cross ventilation. The facade has a surface of 20.6 m<sup>2</sup> to NE (with 23% of window area) and 17.5 m<sup>2</sup> to SW (with 25% of window area).

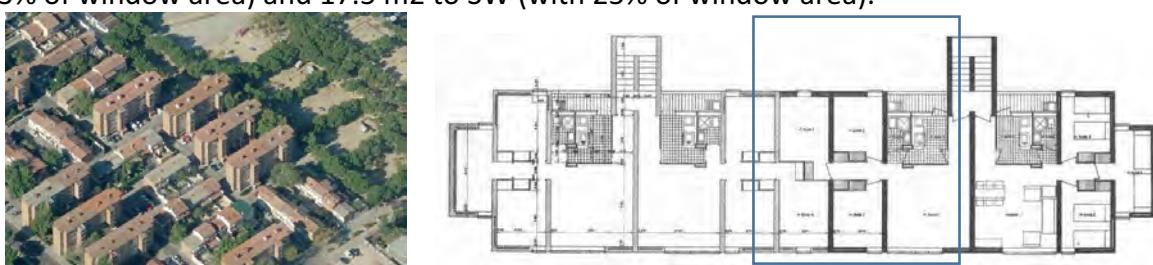


Figure 7. On the left, an image of Social Housing neighbourhood in Manoteras, Madrid. On the right, Social Housing Plan.

### **Definition of samples to be tested**

The composition of the windows follows a scheme quite common in Spanish homes: the original wooden frames have been replaced at some time by aluminium frames with thermal bridge and simple clear glass, later a second window has been added.

Table 2. Samples

	FRAME	GLASS	SOLAR DEVISE
Before (Single o double)	Aluminium	4mm glazing	Traditional louvres
Now	Wood IntelTEK 69	Climalit plus Planitherm XN F2 4(16 argon)4.	Traditional louvres

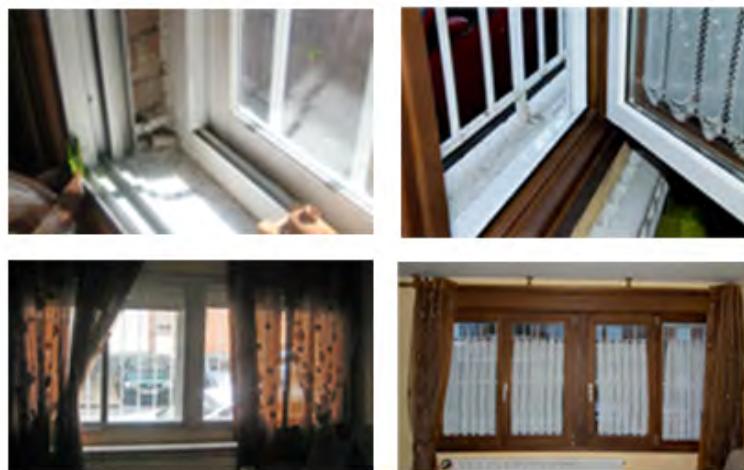


Figure 8. Social Housing windows before and after the renovation.

### **Monitoring**

Non-intrusive IEQ monitoring: air temperature, relative humidity, CO<sub>2</sub>, electrical consumption, heating consumption (Flowmeter).



Figure 9. Monitoring devises.

The heating installation is an individual gas boiler model Themaclassic C 25 Saunier Duval, whose performance according to manufacturer data is 91.5%. It is an atmospheric mixture boiler for heating and instant ACS. The thermostat is in the living room at a height of 1.6m. Setpoint temperatures according to user are: from 8:00am to 2:00pm 17 °C, from 2:00pm to 11:00pm 20°C, from 11:00pm to 8:00am 18 °C. There is no air conditioning or mechanical ventilation system.

### **Results**

Heating consumption during the winter 2015-2016 and the winter 2016-2017 are compared in figure 10, 25% of savings are observed. Exterior temperatures of both winters are shown in figure 11, winter (2015-2016) can be considered milder than winter (2016-2017), nevertheless in December and January the consumption has been similar for those months. In February, average temperatures are similar but minimal temperatures are higher in 2017, which is reflected in a consumption reduction.

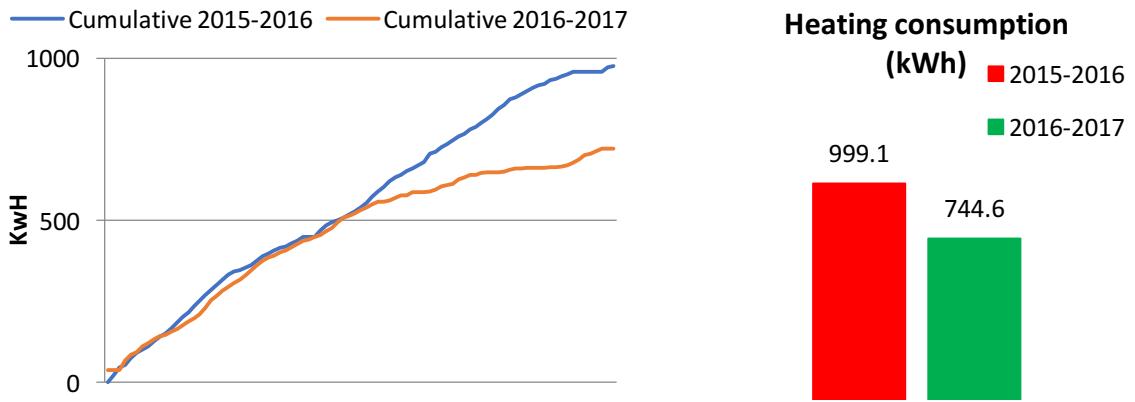


Figure 10. Heating consumption of the winter 2015-2016 and the winter 2016-2017.

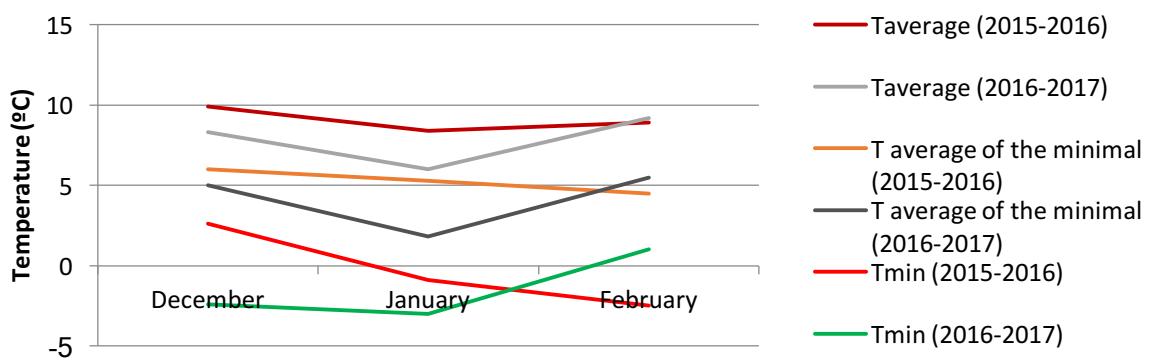


Figure 11. Exterior temperatures (minimal, average and average of the minimal).

CO<sub>2</sub> and HR records show generally higher values since windows have been improved. In Figure 12 the average per day can be observed.

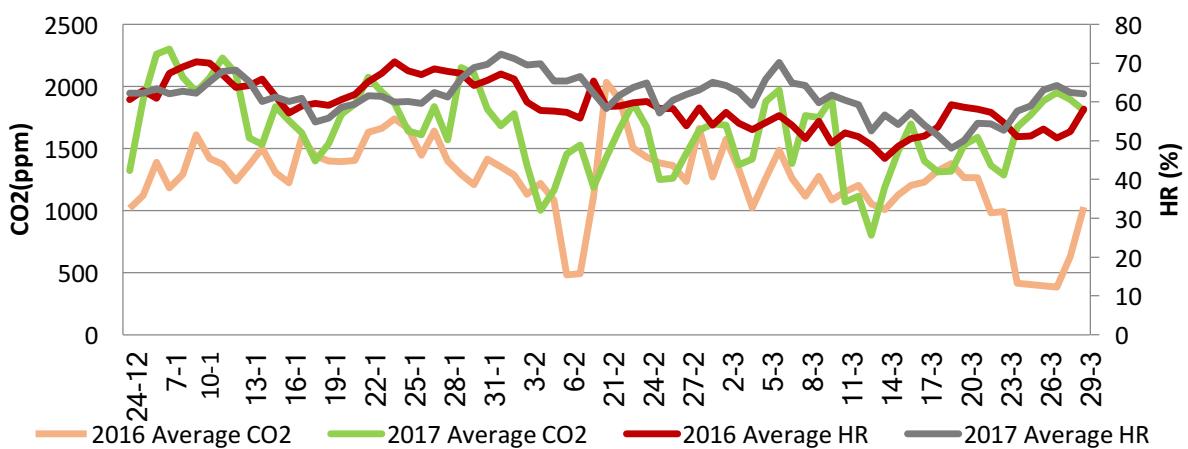


Figure 12. CO<sub>2</sub> and HR average per day.

## Conclusions

Heating savings have been 25% since windows have been improved, which is higher than expected. First hypothesis, considering CO<sub>2</sub> and HR records as well as users reports indicate air infiltrations through windows may have a greater influence than initially thought. Further work is going to be developed in this direction. Before changing the windows a

blower door test was performed, another one will be performed in the same conditions next month. Winter 2017-2018 data will also be recorded and analysed.

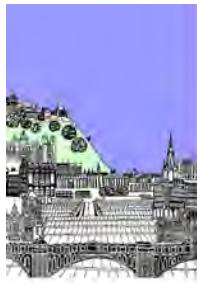
Simulations performed with Design Builder predicted lower heating savings; further work will approach the adjustment of the simulation with real data of the infiltrations and real weather data.

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## References

- IDAE, (2011). Plan de acción y eficiencia energética 2011-2010, Madrid.
- European Commission, (2010). "Directive 2010/31/EU of the European parliament and of the council of 19 may 2010 on the energy performance of buildings", EC.
- Asociación de Ciencias Ambientales,(2012) "Estudio sobre Pobreza Energética en España. Potencial generación de empleo derivado de la rehabilitación energética de viviendas". Proyecto REPEX
- European Commission, (2009). "Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC"
- European Commission, (2009). "Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC (Text with EEA relevance)"
- Bluyssen P.M. (2009) The Indoor Environment Handbook: How to make buildings healthy and comfortable, Earthscan, London, UK.
- Oteiza I.(2017) "REFAVIV. Rehabilitación energética de la fachada de viviendas sociales, con productos innovadores con Documento de Idoneidad Técnica (DIT, DITE). Impactos económico, social y ambiental",
- Carmen Alonso Ruiz-Rivas (2015)"Façade energy retrofitting: methodological proposal for the evaluation of innovative solutions, based on the diagnosis of social housing built between 1940 and 1980", Madrid.
- INE, (2011). Census of population and housing. Instituto Nacional de Estadística. Madrid.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Usability Tool – accounting for understanding and usability in BPE

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**Abstract:** Buildings are increasingly complex; saturated with systems that need coherent controls if design goals are to be achieved. Depending on the typology, users need different levels of control. More research is needed to better understand the cause of ‘unintended’ uses of controls in real buildings. A usability tool (UT) is presented demonstrating new insights into the relationship between design and user interaction with all the available controls in five case study buildings. Experiences from applying the tool in the UK domestic context are compared with a non-domestic application in Mexico City. Several early findings result from this study. Firstly the architects’ involvement in the selection of control interfaces as well as their location in a building is crucial. Also user guidance has to challenge the users’ preconceptions about internal environment controls, incorporating information about the use of specific interfaces and the rationale for using them, showing how they tie in with other elements of internal environment control. Cultural context always needs to be considered and the UT adjusted accordingly when applying the tool in different case studies. The assisted UT has the potential to become a vital learning point for building users. The unassisted UT provides guidelines.

**Keywords:** BPE, home use, user experience, building control, usability

### Introduction

Building Performance Evaluation (BPE) studies have repeatedly found that availability and good use of internal environment controls by the user is key to better building performance and improved user satisfaction (Raja et al., 2001; Bordass et al., 2007; Palmer et al., 2016a). Numerous field studies of low energy homes and offices in a major UK government funded BPE programme have demonstrated a general discrepancy between the modelled and measured energy use observed in buildings and as high as a ten-fold variation in energy use per m<sup>2</sup> per annum; the poor reliability of modelling highlighted the role of user control over internal environment: '*buildings with poor control of space and water heating and/or lighting often had high emissions*' (Palmer et al., 2016b). There is a clear link between underperformance and controls which was further stressed in the summary report of this programme: '*Controls are a problem. There is a tendency to make controls for mechanical and electrical services too complicated. This alienates occupants and can mean the building defaults to high energy use.*' (Innovate UK, 2016b, p.4). Top-down efforts to disseminate design intentions related to the use of environmental controls in a domestic context (Munton et al., 2014) have meant their generic approach is not directly applicable. Home handover tours and user guides are intended to deliver context specific information and skills in relation to systems control and maintenance yet these fail in many cases (Stevenson

et al., 2013; Baborska-Narozny et al., 2016). Using collective learning via social media to improve occupant skills in relation to using controls has become another valid strategy for households within comparable fabric and systems contexts (Baborska-Narozny et al., 2017).

Early ethnographic studies highlight the discrepancy between expert and user understanding of technologies and their control in a domestic context. They reveal surprisingly poor correlation between increased technical correctness and a behaviour that is actually better for saving energy: '*the folk theory that is endorsed by the experts may not work as well in practical day-to-day application. A theory that is useful for designing thermostats is not guaranteed to be a good theory for using them*' (Kempton, 1986, p. 81). Thus, merely passing design intention down the information chain to the user is not always enough to secure 'good use' of controls for a healthy indoor environment with minimal energy input. Recent discourse on building-user interaction in the domestic sector analyses housing case studies through lens of theory of practice (Gram-Hanssen, 2011) or domestication (Hargreaves, 2017). This points towards a need for an in-depth understanding of the context specific user perspective on controls which is only possible through 'real world' research methods e.g. walk-through, surveys or interviews. A recent study in the office environment provides a link between behaviour, satisfaction and a good understanding of how to operate an energy efficient building (Day & Gunderson, 2015), highlighting the need to explore and develop effective educational strategies for building occupants. Our paper addresses this gap directly and proposes an evolved usability methodology (UT) aiming to ascertain user understanding, skills and satisfaction with the controls provided, in order to use and maintain the systems installed. Each stage of methodology development is presented in the following section. The application of the different versions of the tool is introduced next. The discussion on early findings, points towards the architects' role in enhancing better user interaction with controls, the UT role for occupant learning, guidance on learning needs for property managers and a source of feedback for the design and procurement team.

## The Usability Survey

Three evolutionary versions of the UT have been developed to date.

### Version 1

An evaluative tool focusing on environmental controls in a domestic context was first developed in 2011 by Stevenson et al. (2013). It comprised of an expert qualitative evaluation of domestic controls for all the in-built systems and appliances based on a walk though. A matrix dedicated to each control for systems such as heating, allowed rating of usability against a colour coded scale from poor to excellent (Fig.1). The usability criteria considered were: *clarity of purpose, intuitive switching, labelling and annotation, ease of use, indication of system response and degree of fine control*. Each matrix was accompanied by a photo of a control and a comment box. Additionally summary comments covering the overall control of each system were encouraged from occupants. The basic application of the tool by an expert was possible, even in isolation from other BPE methods and tools, by completing a matrix template in situ with relevant data. Depending on the complexity level of the property evaluated this could take a few hours on-site. A report resulting from the walk-through data gives a clear visual overview of the usability of controls. Ideally, however, the on-site visit should be preceded with a design audit to identify any gaps between design

intentions and the as built situation to enhance feedback given to the design and procurement teams.

### **Version 2**

In the next version developed in 2014, the expert based approach was replaced by an interview-based multiple choice user questionnaire with comment boxes to elicit quantitative and qualitative information directly from the occupant. Here it was obligatory to have a prior understanding of all the controls included in a bespoke survey sheet before entering an occupied property for a quick 20 minute survey. The assisted survey did not include any photos this time of the controls, only their technical names. Questions related to user guidance available and maintenance requirements were added. The respondents were also asked to rate their perceived skills in using the technical devices. User interfaces were grouped under the systems they controlled. The new questionnaire covered all environmental home controls – or ‘touchpoints’ of interaction between user and environmental technologies. Each control was evaluated against same criteria as in version 1 with additional criteria for the ‘location’ and ‘understanding of the need for interaction’. The survey questions gave three answer options: ‘Yes’, ‘No’, or ‘I don’t know’. The occupant answered the questions first and the researcher only intervened to clarify the questions if needed taking notes of what was unclear. Any questions related to the functioning of the systems and controls were answered after the questionnaire had been completed. This way the researcher did not influence the survey results.

### **Version 3**

The latest version of the survey developed in 2016 was adapted for completion without assistance for larger samples of occupants. Pictures of controls were added in for clarity and to aid understanding by the occupants.

Table 1. Three UT versions key characteristics.

Usability tool version	1	2	3
...methodology	Walk-through expert evaluation	Assisted occupant survey	Unassisted occupant survey
... criteria considered	clarity of purpose intuitive switching ease of use labelling feedback fine-tuning	clarity of purpose understanding the operation ease of use labelling feedback fine-tuning location understanding of the need for interaction	
...prerequisites of application	Access to a property	Access to a property + understanding of all systems and controls installed	
...on site data collection time	A few hours	Ca. 20min/survey + 20 min. q&a + prep.	A few hours + preparation
...reporting	Immediate visual - colour coded matrices + key comments	Basic - descriptive statistics + key comments Advanced - varied options possible	

### **Case-studies**

Versions 1 and 2 were applied in several residential buildings in the UK (Table 2). Version 1 was applied in two demonstration low energy new built dwellings (case A) as a part two Technology Strategy Board BPE research projects (Stevenson et al., 2013). Similarly Version 2 was applied in conjunction with other BPE methods as a part of an EU funded in-depth evaluation of two residential developments: a low energy new built co-housing development (case B) and a private developer led deep retrofit built to comply with regulations (case C). In both developments the occupants moved in at least 8 months before being surveyed. Version 3 was applied as a stand-alone tool in a university campus in Mexico City, Mexico (case D). The building had been occupied for three years. The research project was funded by The University of Sheffield Global Learning Opportunities in Social Science (GLOSS Associate Scheme) (Baker et al., 2016).

The different levels of energy use targets in the case-study buildings resulted in varying levels of mechanical and electrical systems complexity. For example, cases A and B are equipped with mechanical ventilation with heat recovery and case C has continuous mechanical extract ventilation installed. The Mexican university building by contrast (case D) is naturally ventilated.

Table 2. UT method applications.

Usability tool version	1	2	3
Pilot application			
...date	2011	2014	2016
...number of respondents	2	2x20	102
...location	UK	UK	Mexico
...case-study typology	2x domestic (cases A1, A2)	2x domestic (cases B, C)	Non-domestic (university building) (case D)
...energy standard	EcoHomes Excellent (case A1) CfSH5 (case A2)	Low energy CfSH4 (case B) Reg. compliant (case C)	Reg. compliant
M&E complexity level	Medium (case A1) High (case A2)	High (case B) Medium (case C)	Medium

### **Findings and discussion**

Analysis of qualitative user comments and quantitative surveys results from the three versions of the UT reveals an array of in-use issues with controls that contribute to using them other than intended at the design stage or not using them at all. An additional key source of researchers understanding the context of occupant issues with controls occurred while they assisted the respondents and engaged in an occupant initiated walkthrough to answer questions raised by the survey. Isolated detailed reports and analysis of each UT application were published earlier (Stevenson et al., 2013; Baborska-Narozny et al., 2016a,b, Baker et al., 2016). The purpose of the discussion below is to highlight the key findings arising from consideration of all the UT versions and also to reflect on the impact of the different tools used on the findings as a result.

The causes of the occupancy stage issues with controls can be split into two main groups:

- *Usability* problems due to poor design of specific controls, their inconvenient or unintuitive location.
- Problems with occupant *understanding* due to questions left unaddressed by design, handover and aftercare related to their needs, expectations and skills to control their internal environment.

### *Usability*

The first group of issues is mainly linked with the design and procurement stages flaws. Installing two exactly identical switches next to each other for different functions (one for controlling lights and the other for MVHR boost or a bathroom towel rail (cases B and C) shows poor design team understanding of the usability of such a solution. Similarly, specifying electric radiator panels equipped with a battery powered control panel that dies before the heating season starts and stays non-responsive even after a new battery is provided until a tiny button is pressed with a pin (which only the most inquisitive occupants discovered) resulted in 75% of occupants stating that the control is not easy to operate (case C). Architects have an important role to play in the specification of ‘user friendly’ controls as well as their careful location in a spatial context.

### *Understanding*

However as the UT results show, usability itself may not be enough if occupants are not also familiarised with a system they control. One difficulty with familiarising modern technology is its ‘black box’ operation coexisting with unclear payoffs (Nax et al., 2015). The mechanical extract ventilation (MEV) in Case C was designed to work continuously on low flow rates so as to be unnoticed. The extract fans located on a wall in an open plan kitchen were purposely disguised with a cover to aesthetically match the sleek kitchen design. The isolating switches for the fans were deliberately located by the designer high up in a closed cupboard to discourage any user interaction, whereas the boost button was in an exposed location near the fan for ease of use. However, most occupants found a way to switch the fans off permanently, fairly early on after moving into their homes. In stark contrast to the design intention, the UT survey revealed that 75% of occupants were not aware of the functionality of the visible boost switch on wall – the attempts by occupants to use it did not bring any results as the fans were switched off elsewhere, with no indication of being switched off. A short explanation by the researcher was enough to clarify the MEV operation and boost button link. In a different survey (BUS) two month later, the same sample occupants covered by the UT survey (and subsequent researcher assistance) knew that they had the MEV, while 30% of the population of the development stated they didn’t have it installed, revealing major gap in understanding. In many similar cases the UT assisted survey provided an excellent learning opportunity – the occupants were confronted with their own lack of awareness of certain controls, and were interested to find out what they were misunderstanding. The tool offered a neutral learning medium with no judgement of the occupant.

The learning/understanding aspect of the UT version 2 (assisted survey) also touches on the first group of usability issues with the controls in buildings. The two different methods revealed that the expert driven in-situ evaluation version 1 is more appropriate to pick up the issues linked with usability and location. The occupant misunderstandings in the second group are unlikely to be reliably foreseen by an expert, hence the importance of

asking occupants if and how they interact with controls in daily situations. For example, the thermostatic radiator valve (TRV) was expert evaluated as poor in terms of clarity of purpose and intuitive switching (case A) whereas all the surveyed occupants knew what the control did and whether they should interact with it (case B). On the other hand, a consumer unit received an expert rating of excellent (case A) when 40% of respondents didn't know what the same unit did and whether they should interact with it (case B). A technically inquisitive resident commented that while responding to the UT survey he found that the consumer unit was incorrectly labelled, leading to major health and safety risk. His finding resulted in the residents checking labelling across the development and tracing another faulty label in all 20 dwellings. In daily life, home use controls only occasionally become the focus of occupants' attention - the assisted UT survey provides a rare opportunity for ensuring learning about controls happens. Ironically, expert judgement may be a proxy only for the most technically skilled and inquisitive occupants who actively seek answers in relation to controls, regardless of the information provided at the handover stage or in a user guidance. The large difference in rating of controls by the average and the more inquisitive occupants is particularly visible for the technically advanced interfaces that are new to users, such as an MVHR control panel or boiler control.

The incorporation of the new 'touchpoints' into relevant control practices is linked with an occupant's motivation to learn and adapt, as shown by the correlation between previous contact with controls and the level of their understanding. The controls most familiar to them from their previous accommodation were those best understood. When new systems and controls are introduced, design teams need to facilitate the process by disseminating the design intention, ideally in dialogue with potential occupants, using their tacit knowledge derived from their previous accommodation. For example where a future occupant is unlikely to have any previous experience with continuous MEV and MVHR it is not enough to say in home user guidance '*To maintain the minimum ventilation, the main power to the fan unit should be kept permanently on*' (case C). Further explanation is needed to give a rationale for using the fan here, even though it isn't necessarily needed in a typical leaky home, otherwise the advice will be ignored 'to save energy' or for other reasons adopted by an occupant. There is a vicious circle with lack of occupant interest in home user guidance (half of Case C occupants were unaware of having a home user guide) reinforcing the poorly perceived applicability of such guidance when needed. All the survey results also pointed towards a need for repeated learning opportunities in relation to controls that are rarely used, i.e. emergency controls. This came as a surprise to the researchers - the emergency controls scored very highly in an expert evaluation (case A) but worryingly, 75% of occupants in case B or C could not rate their usability because they had never seen them and didn't even know where to find them. As a result, the occupants took the initiative and prepared a bespoke guide shared with all the households where each emergency control i.e. gas and water stop cocks or fire alarm, etc. was covered (case B). In Case D most occupants were also unaware of how to use the fire emergency equipment if needed. Detailed actionable recommendations of training needs were consequently delivered to relevant university stakeholders following UT survey analysis.

#### *UK vs. Mexican application*

The survey was effective in both the UK and Mexican contexts even though in the later environment research focused on usability of controls in buildings was a novelty. The questions were considered in terms of the specific cultural context and adapted accordingly in order to be well understood, i.e. as the concept of feedback is not well known in Mexico,

the question '*does it show a response to your actions?*' was substituted with '*does this control tell you whether it is actually working or not?*'. In the Mexican university building the controls related to access and security proved to be particularly unusable and misunderstood. This was not as evident in the UK domestic context, where the security controls are generally less complicated.

## Conclusions

Several key findings result from this study of various evolutions of a UT tool in various contexts. Firstly the architects' involvement in the initial selection of control interfaces as well as their location in a building is crucial. User guidance has to challenge the occupants preconceptions about their internal environment controls, incorporating information about the use of specific interfaces and the rationale for using them, showing how the interfaces tie in with other elements of internal environment control. Cultural context always needs to be considered and the UT adjusted accordingly when applying the tool in different case studies. The assisted UT has the potential to become a vital learning point for building users. All UT surveys reveal gaps in occupant training and provide guidance for improvement. The Mexican application of the tool highlights the hierarchy of occupants concerns in relation to their interaction with building controls that go beyond the usability and cover areas such as security.

The UT version 1 was efficient in providing an expert driven overview of the usability of controls as installed in a specific context. The method can be applied without involving the users at any stage of occupancy or even before the handover. In a domestic context this aspect is advantageous, given difficulty with access to inhabited dwellings for research purposes. The major drawback of this method, however, is that it relies on expert evaluation and its results cannot always be regarded as a proxy for occupants' actual perceptions. An expert projects their own experience and expectations towards the evaluated controls. In some cases of evident design and usability flaws these may be quickly picked up and ideally corrected before the user comes in. This builds a case for introducing the UT 1 as a tool for the design and procurement team visiting a site during the commissioning stage. However in less clear cut cases, expert evaluation may be different from that of future occupants, and here the UT versions 2 and 3 maybe more helpful, with pre-planning by the expert, followed by input directly from the occupants. Any tacit gap between the expert expectations and user reality can then be identified and resolved.

Helping occupants to actually achieve satisfactory energy performance in their buildings is beyond the scope of the UT survey. Future research into understanding the link between the use of controls and subsequent energy performance could help to improve energy efficiency per se and should be considered for future iterations of the survey.

## References

- Baborska-Narozny, M., Stevenson, F., Chatterton, P. (2017). Understanding Opportunities and Barriers for Social Occupant Learning in Low Carbon Housing [in:] Littlewood J., Spataru C., Howlett R., Jain L. (eds) Smart Energy Control Systems for Sustainable Buildings. Smart Innovation, Systems and Technologies, Vol. 67. Springer, Chams, 61-87.
- Baborska-Narozny, M. and Stevenson, F. (2016). Mechanical ventilation in housing: understanding in-use issues. *Engineering Sustainability*, 169(4): 125–137.
- Baborska-Narozny, M., Stevenson, F. and Ziyad, F. (2016). User learning and practices in relation to innovative technologies: a case study of domestic photovoltaic systems. *Energy Research and Social Science*, 13, 24-37 <http://dx.doi.org/10.1016/j.erss.2015.12.002>

- Baker, J., Stevenson F., Valeriano, A., Cocom, F. (2016) Evaluating the usability of control interfaces in university campus buildings: A case study in U.N.A.M, Mexico City (University of Sheffield report – unpublished)
- Bordass, B., Leaman, A., Bunn, R. (2007) Controls for end users; a guide for good design and implementation. Reading: Building Controls Industry Association. [www.bsria.co.uk](http://www.bsria.co.uk)
- Badura, A. (1977). *Social Learning Theory*. New York: Prentice-Hall.
- Building Services Research and Information Association (BSRIA) (2009). Condensing boilers and domestic heating controls. <http://www.bsria.co.uk/news/dom-controls/>. Last accessed May 2nd, 2013.
- Day, J., Gunderson, D. (2014) Understanding high performance buildings: The link between occupant knowledge of passive design systems, corresponding behaviours, occupant comfort and environmental satisfaction. *Building and Environment*, 84, pp. 114-124.
- Gram-Hanssen, K. (2011) Understanding change and continuity in residential energy consumption. *Journal of Consumer Culture*, 11(1), pp. 61-78.
- Hargreaves, T., Wilson, C. & Hauxwell-Baldwin, R. (2017): Learning to live in a smart home. *Building Research & Information*, DOI: 10.1080/09613218.2017.1286882
- Munton, A.G., Wright, A.J., Mallaburn, P.S., & Boait, P.J. (2014). How heating controls affect domestic energy demand: A Rapid Evidence Assessment. A report to the Department of Energy and Climate Change. DECC, London.
- Kempton, W. (1986) Two theories of home heat control. *Cognitive Science*, 10, pp. 75-90.
- Nax, H.H., Burton-Chellew, M.N., West S.A., Peyton Young H. (2016) Learning in a black box. *Journal of Economic Behavior & Organisation*, 7, pp. 1-15.
- Palmer, J., Terry N., Armitage P. (2016a) Building Performance Evaluation Programme: Findings from non-domestic projects, London: Innovate UK.
- Palmer, J., Godoy-Shimizu, D., Tillson, A., Mawditt, I. (2016b) Building Performance Evaluation Programme: Findings from domestic projects. London: Innovate UK.
- Raja, I.A., Nicol, F.J., McCartney, K.J., Humphreys, M.A. (2001) Thermal comfort: use of controls in naturally ventilated buildings. *Energy & Buildings*, 33, pp. 235-244.
- Stevenson, F., Carmona- Andreu, I. & Hancock, M. (2013). *The usability of control interfaces in low-carbon housing*. *Architectural Science Review*, 56, pp. 70-82.
- Yin, R. K. (2009). *Case study research: Design and method*. 2<sup>nd</sup> ed. London: Sage.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The performance under the ergonomic approach of building icons of Brazilian modernist architecture in São Paulo, built between 1930 and 1964: buildings for commercial and service use

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**Abstract:** The objective of this article is to show the results obtained so far, in the evaluation of the performance, under the ergonomic approach, of the buildings of the Brazilian modernist architecture, in São Paulo. These are: Conjunto Nacional Building (1963), designed by David Libeskind; Itália Building (1964), designed by Franz Heep and Copan Building (1964), designed by Oscar Niemeyer. The purpose of the research is to understand the interrelationships of ergonomics with other areas of environmental comfort (lighting and thermal). Moreover, it intends to assist in understanding the overall performance of buildings, both in physical space and in environmental aspects. In this way, it evaluates not only the adaptations made for greater functionality that occurred during the useful life of the buildings, but also the users' expectations about WORK activity. The method used in the research is inductive experimental with field research of physical and environmental variables. The results are analyzed in a comparative way between the experimental data of the buildings in their current settings and design, combined with ergonomic performance criteria. Until now, the research indicates that some buildings have been modified from the original floor plan which have compromised their proper performance, hampering the comfort conditions and aggravating the dependence on active strategies of environmental conditioning.

**Keywords:** Brazil Modern Architecture, Ergonomic Comfort, Evaluation, Performance , Project.

### Introduction

The buildings, icons of Brazilian modernist architecture, chosen for this research were: Conjunto Nacional (1963), designed by David Libeskind - Figure 1; The Italia building (1964), designed by Franz Heep - Figure 2 - and the Copan building (1964), designed by Oscar Niemeyer - Figure 3. These are examples of the application of design strategies with regard to shape, building orientation, façade shading, openings for natural ventilation and natural lighting. Also, the use of the structure and other constructive components such as thermal mass for the control of internal temperatures, among other environmental characteristics and purposes.

Brazilian architecture of this period, therefore, is also known as bioclimatic architecture (CORBELLA and YANNAS, 2003), due to its climatic insertion characteristics. This aims to control solar radiation, natural light, natural ventilation and temperature fluctuations with the use of the inherent thermal mass, which is mainly the concrete structure. Together, the three buildings selected as case studies of this research bring

together architectural solutions that summarize both the essence and the diversities of the acme of the Brazilian modernist architecture of the commercial building.

The intention of including examples of commercial architecture as case studies comes from the fact that these are the architectural functions that correspond to the largest number of buildings in the city, which have distinct requirements of environmental comfort and also different design solutions. In addition, they are considered constructions that added value and brought identity to the brazilian commercial buildings and residences.

Concerning the environmental scope, for ergonomic performance evaluation, aspects of thermal performance and luminosity were included, since they interact with each other, at the same time they should be evaluated according to the functionality of the space. Even today it is little known about the qualitative and quantitative performance of these buildings and their particular solutions, designed to handle with the users demands regarding the environmental comfort.

Using on-site measurements and interviews with the building users, it is possible to formulate an insight about the current performance of these buildings according the current comfort requirements. Complementing this analysis, with the ergonomic evaluation, it can be learn about the performance of the building when it was designed, in the original floor plan with no possible changes and, above all, in the original situation of the built surroundings.

Based on case studies in the city of São Paulo, this research focuses on learning about the ergonomic performance, quantification and qualification of the commercial and residential buildings of brazilian modernist bioclimatic architecture, between 1930 and 1960. In addition, it seeks to understand the interrelations of ergonomics with other areas of environmental comfort (lighting and thermal) and to help in understanding the overall performance of buildings. Therefore, analysing the adaptations made for greater functionality, in the physical space and in environmental aspects in order to relate with the expectations of the users regarding the WORK. From these data, will be formulated architectural recommendations for the environmental suitability of contemporary projects.



Figure 1. Conjunto Nacional building



Figure 2. Itália building



Figure 3. Itália building

## Ergonomics

The insertion of environmental comfort, the focus on ergonomics, the design and evaluation of architectural projects and existing buildings, the questioning and the redefinition of an "environmental comfort", which, despite its specificities, Influenced by values of convenience, Adequacy, expressiveness, convenience and pleasure (VIRILIO, 1993). This perception encompasses not only all its variables and interferences, but also several behavioural factors, which were marked in four large structuring groups: social, cultural, psychological, environmental and physical (SHMID, 2005).

One thing that can be criticized about this approach is it's deepening and level of details in terms of the physical factors instead of others. This occurs once the project is usually restricted by aspects such as anthropometry and accessibility. The core of the project, thought, is define Ergonomics role, not only as one of the areas of environmental comfort, but also in its real part: design, structuring and evaluation of projects

Ergonomics come up in the after war period - 1972 - with the basic goal of improve the factories working conditions at a time when large production and limitless physical efforts were common. For a long time it were connected exclusively to dimensional, anthropometric and, most recently, accessibility matters. Despite it, understanding work as any man's action in its environment brought the real state of ERGONOMICS.

Based on the assumption that Ergonomics in Architecture has man as object in space, it can be defined as the study of the actions and the mutual influences between human being and space through reciprocal interfaces. In this way, the contribution of ergonomics in architecture is to propose relations and conditions of action and mobility, to define proportions and to establish dimensions in specific conditions for natural and constructed environments. It is based on environmental comfort, which presupposes the individual perception of qualities, influenced by values of convenience, suitability, expressiveness, comfort and pleasure.

Based on these assumptions, ergonomics, using its four structuring factors, supports design actions that aim for comfort, and these are: the measurable and the non-measurable. They are object of study of Ergonomics applied to Architecture and Urbanism.

In general, environmental comfort is not yet adequately addressed in most Brazilian building projects. When assessing the urban context, the quality of spaces and the insertion of these in the city, the situation are similar. In spite of this, the icons of Brazilian

modernism analyzed are known for aspects related to environmental comfort. Thus, such studies can provide great insight into the design techniques of comfort and ergonomics.

### **Modernist Architecture**

The Copan building (1964), in the downtown district, is currently composed of a two-volume building complex, with a horizontal base for commercial use and a vertical tower with 32 floors for residential use. It was designed as a stretch of the city in order to constitute a great urban equipment, since it concentrates a big diversity of equipments configuring a "vertical city". The original design had humanistic characteristics with a well integrated architectural set that consisted in a horizontal volume with commercial and services uses and two blocks - a rectilinear, intended to be a hotel, and another curve, intended to be residential. The design of the building aimed to articulate the building with the city so that the sidewalk floor invaded the building as an extension of the city.

The variety of types of habitations along the curved block comprehends typologies from smaller areas, the kitchenettes, to the larger ones, the apartments with 3 bedrooms. In the original project there were 5 blocks A, B, C, D and E. The block A was planned to be for kitchenettes with a long internal corridor, the block B, C and D were apartments with three bedrooms, with differences between the areas. Blocks E and F, were the larger, with apartments between 3 and 4 bedrooms.

The approved design had tremendous differences from the original design. Some more significant changes were: the rectilinear block, initially thought to be a hotel, was changed to be a Bradesco bank. Also, the apartments in block A were divided into two more blocks one with two bedrooms and the other with kitchenettes.

In aspects of design and environmental comfort Copan was the first building to be approved by the prefecture with internal sanitary and forced ventilation. This due to the demand for small apartments created by the urban expansion and housing deficit. For solar protection, the main façade of the building was designed with horizontal "brisés soleil" (a common type o shader element in the brazilian modernist architecture) with 1.45m wide and spaced 1 meter apart. These brises had not only the function of shading but also, they play a fundamental role in the formal characterization of the building. In addition, on the back façade was used the hollow brick wall, cobogó, that shades and ventilates the environments.

Another architectural complex of the period, in the city of São Paulo, was Conjunto Nacional (1963), comprising the residential and commercial function in a single high tower, over a horizontal base of commercial and public use, with a garden terrace between the base and the tower (IACOCCA, 1998). The Conjunto Nacional architecture have the hollow brick wall elements, cobogó, a narrow floor plan, a combination of opaque parts and glazed parts on the main façades, solar protection for the blocking of solar radiation (brisés soleil) and the control of natural light . In addition, facing Avenida Paulista, the Conjunto Nacional is oriented north and south, which favours the natural lighting of the building.

The project was thought to be an extension of the street, therefore, there are access through the streets that border the building and the sidewalk floor get in the commercial bloc. The Conjunto Nacional was designed for cellular offices and is occupied in this way until today. It inaugurates the occupation of Avenida Paulista and it was the first one with such dimensions. It is distinguished by its type of occupation and design in which the limits of the block are the limits of the building itself. The original design has passed by major changes. Initially, it was planned, a horizontal commercial bloc and a vertical bloc divided

into two functions, a hotel and a commercial complex. Also, movie theater, a theater and a garden terrace were also designed.

The Italian Circolo Building, better known as the Italy Building, 1956, was for a long time the largest building in the city of São Paulo, with 165 meters high. It is mostly occupied by offices, but also has, on the first three floors, the Italian Circolo Association which has a library, a games room and a theater. With 44 floors plus a basement and 19 elevators, its 52,000 square meters has a capacity for 10,000 people and a floating population of 25,000 people.

The implantation of the building, on the corner of Av. Ipiranga and Av. São Luiz, facing the Republic Square, was decisive for the building project to be approved by the prefecture as a landmark of the city. Following the same logic of Conjunto Nacional building, the Italia building is based on a basement bloc and a vertical volume. To cover the gables of the adjacent buildings, the architect designed two narrow blocs with eight floors - this was the height allowed for buildings at the plot land boundary at that time - coated with glass blocks with framed windows.

The Italia building was considered a pioneer of the brazilian large buildings both in the constructive technical way and in the architectural way. One of the innovative solutions for that time was the vertical circulation made through 19 lifts, 5 for exclusive use of the Italian Circolo and 14 for common use. To rationalize the supply system, at each interruption of a group of elevators the two subsequent floors receive their engine houses and water tanks.

The flexibility of the building's office floors is ensured, mainly, by two factors first the hydraulic and electrical installations that run around the perimeter of the building, guaranteeing freedom in the location of the toilets and in the offices layout. Second, the structural system adopted - the building has 12 pillars and four structural walls besides the column of elevators that has structural function. The small number of pillars occurs due to the distribution of the cargo weight by more than one hundred pillars located in the perimeter of the ellipse. These also have the function of bracing, allowing a building with the size of the Italian Circolo has an immense freedom and an open floor plan.

## Search and data

A bibliographical research was made to obtain significant work in the area and academic research for concrete results on ergonomic evaluation. Therefore, the concepts and proposals were analyzed, to deepen the theme and confirm its complexity. Two works were more used for the research: *Habitar El Presente*, by Josep Maria Montaner and Cláudia Andrade's *History of the Work Environment in Office Buildings*. In addition, the master's thesis "The Importance of the study of functions and activities in the design and dimensioning of housing", by André Luiz Souza Barbosa, which presented an evaluation method with a table that proved to be adequate for the work in this research. The table facilitates an ergonomic inventory to evaluate the interior of the buildings based on the description of the activities performed by each user. This description is classified by the nature of the activity, location, and the user's classification.

Also, technical data and design data were searched in books and collections in order to obtain information (technical detailing and design drawings) on the current situation of the studied buildings, as well as its original floor plans. It was possible to find technical drawings from various periods of the buildings, so specific bibliography was used for each one. Public collections of architectural drawings and a library of projects were also consulted at FAUUSP. The plants that were deteriorated by time were transferred in 2D and

3D softwares. This methodology is important for the understanding of functions and use activities in commercial buildings and services. They also act as an instrument of understanding project design as they simulate the possible demands and paths of users in a certain environment.

### **Field research and ergonomic performance analysis**

Three buildings were selected to carry out this research. For each one, a sufficient number of users were calculated to carry out valid measurements and questionnaires. For the Copan six apartments were elected; for the Conjunto Nacional three distinct offices and for the Italia Building two offices on different floors. In addition, questionnaires (ergonomics, thermal and light comfort) were applied to the residents and comfort measurements - Figure 4 and 5 - were taken of the surroundings and the most used spaces by the interviewees. In addition, it was conducted surveys for ergonomic assessment, which resulted in a series of data and tables from where it was possible to generate charts and diagrams. Computational simulations were also made in the ambience - Figure 6 - in order to understand the environmental conditions.

In the evaluation of the interior of the buildings the ergonomic analysis basically covers 03 phases. The first focuses on the task analysis - uses and functions of ambiences - of obstacles and task study. In the second phase the anthropometric analysis of the task is performed - Ergokit application and Julius Pañero's anthropometric database - assessment of the suitability of the environments and dimensioning for the activities. Finally, the third phase is the inventory of the furniture used and the comparison with modifications made from the original design as well as recommendations for ergonomic comfort.

The field research was made in the three buildings selected between 03/18/2015 and 04/14/2015. Researches were also carried out in the external area of buildings with the objective of obtaining comfort data, user opinion and ergonomics of the surroundings. With the data obtained in the measurements and questionnaires it was possible to start initial analytical procedures for the performance evaluation with ergonomic approach of the buildings.

From the floor plans, it was verified that all the three buildings were intensively modified over the years. The offices changed both the ideological concept and the layout. This may be associated with comfort issues, cost and doctrine issues, or even both. Moreover it was possible, from the design bases, to verify qualities and possible design problems that can interfere with the user's daily routine.

In the Circolo Italiano building the 13º and 33º floors were measured, mainly, where formal changes and layout were observed. Both evaluated floors changed their design to an office of closed rooms, hierarchical, without spaces of integration of free plans, without partitions and with more integrated layout. Both offices evaluated at this stage had furniture arranged on a regular way, however, with differences in the type and style of the furniture. On 33th floor the furniture was more similar to workstations with folding screens, furniture attached and few variations. While on the 13th floor the furniture was self-supporting with separation between the folding screens and the furniture.

Another important finding from the measurements was the pavement performance, since, in the cases studied, there was both mechanical ventilation and air conditioning. In the case of air-conditioned pavement, the thermal performance of the pavement showed a worse condition of comfort compared to the one with natural ventilation.

In the Conjunto Nacional Building were measured three rooms - one on the 5th floor and two on the 23rd. The rooms have also been changed from the original plants, but the change is less drastic compared to the previous case. The number of tables and occupants has been increased so that the rooms, previously intended to be a part of an office now has an entire staff. In addition, the rooms on the 23rd floor presented problems in the layout of the office since there is light reflection in the work area obfuscating the user and disrupting the work. This interferes with the use of shutters and air conditioning system.

In the Copan building the plant changes were the most radical. The measurements were made mostly in Kitchenettes which allowed the evaluation of the minimum space of a house, as well as of conflicts resulting from the disposition of the furniture. Furthermore, problems with ventilation and lighting have been repeatedly identified since, depending on the exposed façade, the apartment receives a lot or very little natural light.

In the coming months there will be more visits to offices and apartments with the FAUUSP LABAUT team. During these visits, questionnaires and interviews will be applied in order to better understand the activities carried out in the offices. There will also be ergonomic measurements of the locations so that it is possible to evaluate the workspace. With the data obtained by ergonomics measurements we intend to create a diagram of influences of the activities performed and the space required for them.

## Conclusion

The results obtained so far indicate that some buildings have experienced changes in relation to the original plan that have compromised their adequate performance. The analysis indicates that many of these modifications, in search of greater "functionality" besides impairing the adequacy of the environmental variables, made also the dependence of active strategies of thermal conditioning and lighting worsened the overall performance of the buildings. Other buildings, which maintained the original design without major alterations, are able to maintain today a higher environmental quality. Another point to be analysed in relation to the performance of buildings is the interaction between the user's behaviour in the ambience and the ergonomic suitability for offices and homes that are a need to meet the best performance goals.

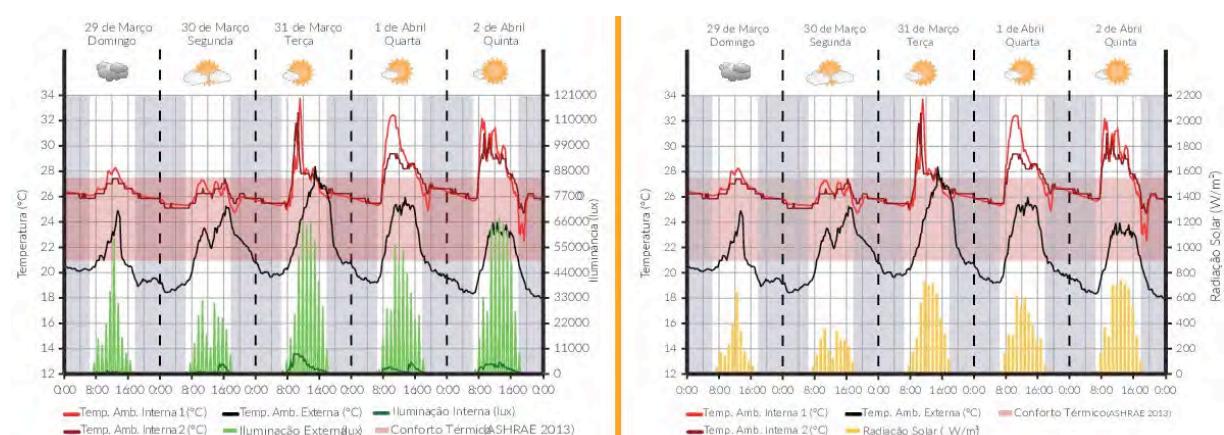


Figure 4. Examples of measurements made from Conjunto Nacional (external temperature, solar radiation, internal temperature, internal illumination and external illumination)

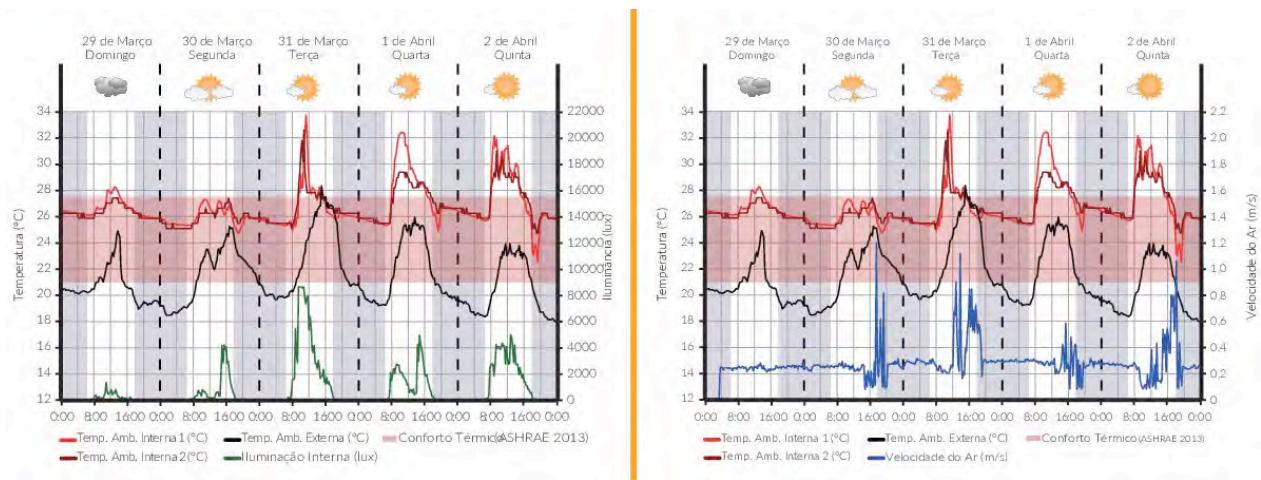


Figure 5. Examples of measurements made from Conjunto Nacional (external temperature, solar radiation, internal temperature, internal illumination and wind)

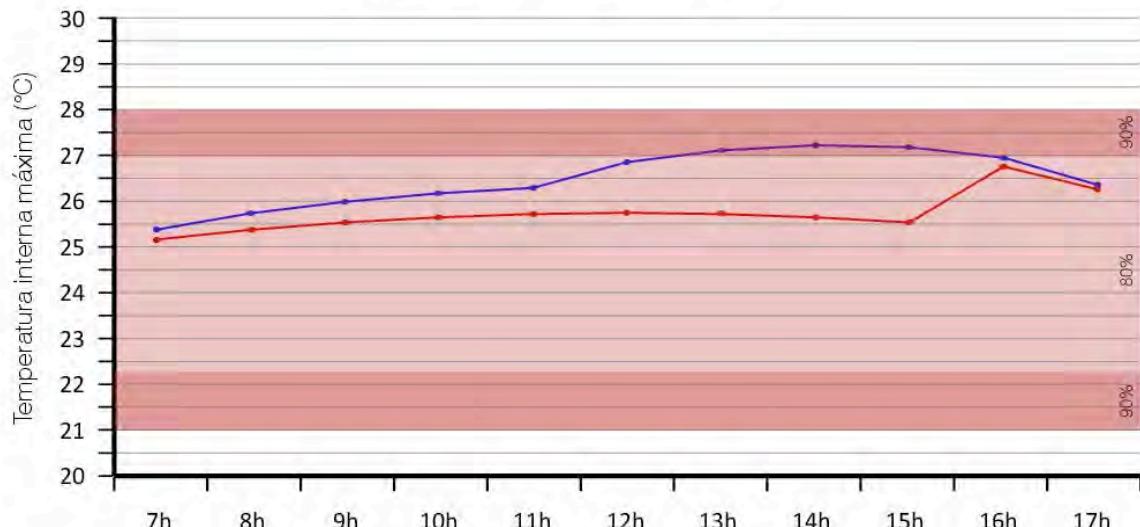
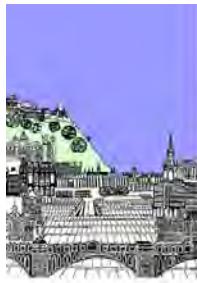


Figure 6. Examples of simulation made for Copan building (red line - apartment with brise solei - and blue line - apartment without brise solei - in the parameters of ASHRAE 2013)

## References

- Cambiaggi, S. (2004) Universal Design: Teaching Methods and Techniques in graduation of Architects and Urbanists. Master Thesis - FAUUSP.
- Iacocca, A. (1998) Conjunto Nacional Assembly: The Conquest of Paulista. São Paulo: Publisher Peirópolis Foundation.
- Montaner, J., Martínez, Z. (2006) To inhabit the Present. Housing in Spain: society, city, technology and resources.
- Andrade, C. (2007) The History of the Work Environment in Office Buildings: A Century of Transformations.
- Andrade, C. (2005) Evaluation of performance in office buildings: the work environment as a means for productive well-being. PhD Thesis.
- Schmid, A. (2005) The idea of comfort: reflections on the built environment. Curitiba: Environmental Pact.
- ABNT. NBR 9050: 2004: Accessibility to buildings, furniture, equipment Urban Rio de Janeiro, 2004. 97 p.
- Johnson, S. (2001) Culture of the interface: how the computer transforms our way of creating and communicating. Rio de Janeiro.
- Panero, J., Zelnik, M. (2006) Human Dimensioning for Interior Spaces.
- Roman, E. (2003) Business space management methodologies: New guidelines for the design of work environments.
- Sader, A. (2003) Office space: new looks about concepts and Forms. Monograph.
- Barbosa, A. (2007) The Importance of Studying Functions and Activities in the Design and dimensioning of housing. Thesis for graduation, FAU-USP.



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*Design to Thrive*



## How user practice and habits impact the energy consumption in nearly zero energy youth housing in Denmark

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**Abstract:** Several projects constructed during the last years demonstrate that it is possible to design buildings which can be defined as “zero-energy buildings”. However, research show that it can be difficult to meet the expected low energy consumption. Studies suggest that one of the reasons for this is that occupants’ behaviour and lifestyle strongly influence the final energy consumption. This paper presents a preliminary study of a larger research project that studies the relation between energy use and user practice and habits as well as the users’ expectations to and experiences of living in a newly built nearly zero-energy youth housing complex in Denmark. The objective of this study is to examine to what extend user practice and habits influence the energy consumption and on that basis to identify representative user characteristics within this specific user group. Methodologically this is done through a case study where data on measured energy consumption for space heating is juxtaposed with the results of a questionnaire survey. The study indicates that variations in heat consumption across the apartments are not primarily related to apartment type, orientation or floor, but rather related to the inhabitants’ use of their apartment.

**Keywords:** sustainable architecture, inhabitants’ daily practice, youth housing

### Introduction

Although it is still not common practice, several projects built during the last years demonstrate that it is possible to design buildings which can be defined as “zero energy buildings”. However, research shows that low-energy buildings do not always live up to the expectations, among others due to discrepancies between the expected (calculated) energy need and the actual (measured) energy use after commissioning (Larsen & Brunsgaard 2010). Studies suggest that one of the reasons for this is that occupant behaviour strongly influences the energy consumption of buildings (Gram-Hanssen, 2010, 2013 & 2014, Steemers & Yun, 2009). Therefore, as accounted for by Gram-Hanssen (2013), there has been an emerging interest in documenting the importance of user behaviour on buildings’ energy consumption, also within more technical oriented research. In a study performed by Steemers and Yun (2009) it is clarified that the second most important parameters that determines energy use relates to occupant behavior, especially related to the choices made about heating and cooling systems and the control of these. Steemers & Yun conclude: “The central role of occupant and behavioural aspects is evident and is essential for understanding, evaluating or predicting building energy use” (Steemers & Yun, 2009, p. 635). Furthermore, studies suggest that there is a trend towards that people adapt their comfort to the type of housing they live in, i.e. in old houses one typically put on a sweater and slippers in wintertime, whereas one who lives in new low energy houses wears a T-shirt all

year long (Gram-Hanssen, 2015). Hence, the expected energy savings in low energy houses risk to be absorbed in increased comfort. However, is this trend general for all user groups?

Current paper presents a preliminary study of a larger research project that studies the relation between energy use and user practice and habits as well as the users' expectations to and experiences of living in a newly built nearly zero energy youth housing complex in Denmark. The building is a 99 apartment youth housing complex classified as a nearly zero energy building (nearly ZEB) and several passive and active strategies have been applied in order to minimize the energy demand, including among others: high-insulated and air-tight building envelope, natural ventilation as passive cooling, mechanical ventilation with heat recovery, and heat recovery of the domestic hot water (DHW). The 99 apartments are relatively uniform as regards type and size. The inhabitants are young people who are all enrolled in education. Hence, the group is relatively homogeneous and shares many conditions. On this basis, it is presumed reasonable that the study can lead to an identification of typical user characteristics. Therefore, the objective of this study is to examine to what extend user practice and habits influence the energy consumption and on that basis to identify representative user characteristics within this specific user group.

### ***Background information***

The youth housing complex was built in 2011-12 and was the winner of an invited turnkey contract competition put out to tender by the Danish housing association Ringgården. According to the energy labelling report the building complies with the current Danish 2020 requirements (the demand for energy supply for heating, ventilation, cooling and DHW per m<sup>2</sup> of heated floor area must not exceed 20 kWh/m<sup>2</sup> per year (Bygningsreglementet.dk, 2017: 7.2.4.2) and has a calculated surplus production of energy of 7.3 kWh/m<sup>2</sup>. The majority of the apartments have two-rooms and a net area ranging from 29.6 m<sup>2</sup> – 33.6 m<sup>2</sup>. There are only 5 one-room studios with a net area of 28.6 m<sup>2</sup>. The building has 12 stories (excl basement and garret), floor-to-ceiling height is 2600 mm, and the building is supplied by district heating. The building is one out of four high-rise youth housings placed close together at Aarhus (DK) waterfront. South-east (SE) of the building is a 12-storey high-rise, towards west (W) is a 9-storey building and towards north-west (NW) a 6-storey building.

### **Methodology and data**

The inquiry is based on a holistic single-case study (Yin, 2003) using a mixed methods approach (Bryman, 2012) to reach a nuanced understanding of the case. The data applied are drawings of the building, descriptions of the building, meter readings of energy consumption and a questionnaire survey sent to the tenants. The questionnaire has been composed in the software program SurveyMonkey (2017) and was sent to the tenants by email containing an invitation to participate in the survey and a brief introduction to the topic and themes in the questionnaire. The addresses were provided by Ringgården, the tenants could answer the questionnaire online and respondents were promised anonymity. Two reminders were sent to the tenants who had not answered in order to collect more answers before the deadline. The participation in the questionnaire was voluntary but among the responses two winners of 2 x tickets for the cinema was found by draw.

### **Data**

The measured data is based on meter readings of the 99 apartments' energy consumption. The meter readings are provided by the housing association Ringgården whom has

constructed and runs the building. The housing association logs systematically the energy consumption of each apartment for space heating, cold water, domestic hot water (DHW) and electricity every day, all year round. The data used in this paper is the sum of daily meter readings of the 99 apartments' energy consumption for space heating, measured over two years; 2014 and 2015. The validity of the study is thus assuming correctness in the data received from the housing association. The energy consumption for space heating is not adjusted for degree days since the primary objective of this study is to get an overview of the level and variation of energy consumption for space heating for the 99 apartments and not to compare the two years. Year 2014 and 2015 are, however, relatively comparable since both years were mild. According to the Danish Technological Institute (TI) the number of degree days in 2014 and 2015 was 2100 and 2278 respectively. Compared to TI's "average year" with 2906 degree days this means that the energy consumption for space heating in 2015 could be expected to be 21% lower compared to an average year but 8% higher than 2014 (Teknologisk.dk, 2017). Likewise, as the study focuses on the apartments and the impact of the inhabitants' behavior and habits on the energy consumption, the energy consumption related to the overall building operation, including common facilities and areas, is not included.

The questionnaire survey has been distributed to 95 of the 99 inhabitants, four had just moved in and for that reason ruled out. 49 responses were received but two of them where insufficiently filled out. 47 inhabitants completed the survey; hence the response rate is 49.5%. The questionnaire aims to gather knowledge of how the inhabitants use their apartment, for which reason they are asked about how much time they spend there, if they prefer different temperatures in different rooms, and their practices in regard to adjusting the indoor environment, etc. The study is based on the assumption that the 47 responses of the questionnaire survey are representative for the user group. If not otherwise specified n=47. The survey results are stated in round numbers. Instead of comparing the 47 responses with specific data on energy consumption of the respondents' apartment, it is chosen to compare the responses with the larger data set of measurements on all 99 apartments. One reason for this is that not all 47 respondents have lived in the building for the entire period when the measurements have been collected (at the beginning of 2014 to the end of 2015), since the inhabitants must enrolled in education. Of the 47 respondents nearly 80% lived in the apartment for all or part of the period in which measurements are collected. The main motive is, however, that the aim is to clarify *tendencies of this specific user group* rather than to describe the particularities of individual users.

## **Results and discussion**

In order to reach a deeper understanding of what characterizes this specific user group, it is first and foremost interesting to clarify why they have chosen to live in this nearly zero-energy youth housing. The respondents were asked about what the reason(-s) for choosing to apply for an apartment in this particular building were. The respondent could give more than one answer; hence, the sum is not 100%. The options were: The location of the building near Aarhus city centre; The location of the building near the water; Because it is a new building; Because the building as a nearly ZEB; Close to place of study; Close to family; The architecture; The size and/or layout of the apartment; The common facilities; Because I knew one who lived here; It was the apartment I was offered; and Other (please note).

The reasons that had most influence on their choice is the location of the building near the city centre (83%) and by the water (49%), as well as the inhabitants place of study

(55%), but also the fact that it is a new building (70%) and simply because it was the apartment they were offered (49%). Only 8 out of 47 respondents (17%) it was a causal factor that the building is categorized as a (nearly) zero-energy building (ZEB). When asked if they knew that the building is a nearly ZEB, 4/5 of the respondents reply that they were aware of it, but only 24 respondents (51%) answer that this means that they have particular expectations to the building. Generally the supplementary comments that elaborate expectations related to the low energy standard of the building are the expectations of lower consumption and costs. 31 respondents (66%) also reply that they feel they have the opportunity to influence their heat and electric bill through a resource-conscious behavior, whereas 5 respondents (11%) do not feel they have an impact on the bill and 11 respondents (23%) reply "don't know". The latter might indicate that they are either not conscious about their behavior; about how their behavior could influence it; or perhaps it just does not interest them. When asked about to what extent they generally are concerned about saving energy, 10 respondents (21%) answer "to a great extent" and 24 (51%) answers "to some extent", whereas 8 (17%) reply "neither/nor" and 5 (11%) "to a little extent" or "not at all".

All in all, the results here indicate that a clear characteristic of this user group is their appreciation of being close to the city centre and that the location for the majority in general means a lot. By comparison, the low-energy standard of the building only seems significant to a part of the group. Generally, the results seem to identify two sub groups in the otherwise homogeneous group; one group to whom the low-energy standard of the building is significant which also means that the group have specific expectations to it; and one group to whom the energy standard seems relatively unimportant, whether this is due to lack of knowledge or lack of interest. The first group seems to be covering the majority; this is also supported by the fact that more than 2/3 consider themselves to be generally concerned about saving energy.

Looking at the energy consumption for space heating of the 99 apartments in 2014 and 2015 (figure 1), we see that the heat consumption is virtually the same the two years and so is the variation across the apartments. When data for 2016 are released the validity of this tendency can be further examined.

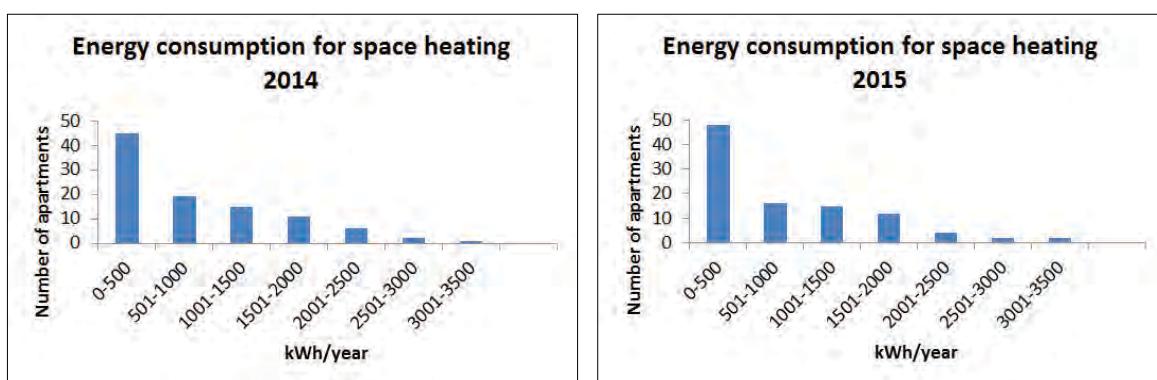


Figure 1. Heat consumption of the 99 apartments, classified in intervals of 500. Not adjusted for degree days.

In 2014 45% and in 2015 48% of the apartments had yearly energy consumption for space heating between 0-500 kWh. 45% and 43%, respectively, had yearly energy consumption between 501-2000 kWh and well over 9% and 8% of the apartments had a consumption between 2001-3500 kWh which is minimum 4 times higher than almost half of the

apartments. If we look deeper into the numbers we see that in 2014 4 apartments actually did not use any energy for space heating at all and in 2015 this number had increased to 20 apartments. Hence, the measurements show that the energy consumption for space heating in this building is generally very low; even with 20% using 0 kWh in 2015, but compared with and in contrast to this, a smaller amount of apartments have quite high heat consumptions; a few even more than 3000 kWh. The generally low heating demand is expected since the building fulfill the energy demands for the Danish building class 2020 and may be explained by the compact building form, the high-insulated and air-tight building envelope, and the fact that both years were mild (as described earlier). However, can the building physics also explain the higher heating consumption of the 8-9% of the apartments?

The data show that two of the apartments with the highest heat consumption is placed on the 1<sup>st</sup> floor (level 0) at which the higher consumption may be explained by a higher heat loss towards the basement. However, the neighboring apartment has a heat demand of approx. 780 kWh in 2014 and 0 kWh in 2015. Likewise, two other apartments with a heat demand above 3000 kWh are placed on the 3<sup>rd</sup> and 10<sup>th</sup> floor. The four apartments which have the highest heat consumptions are oriented towards NW, E, E and SE. The tall neighboring buildings towards NW, W and SW will of course shade from the sun, but the apartments with the highest heat consumption are not placed in particularly shaded places of the building. Likewise, if we look at the apartments with a heat consumption of 0 kWh, there do not seem to be a pattern in type of apartment, orientation, or area of external envelope. The majority of these are placed on the 5<sup>th</sup> floor and above, however, apartments with generally low heat consumption up to 500 kWh occur fairly evenly distributed in the floors. Summing up, there are only four apartments that have heat consumption above 2400 kWh in both years and these are located in the bottom, the middle and the top of the building and towards different corners of the world. It is not possible to draw an absolute conclusion on this basis; nevertheless, the data indicate that neither orientation nor the floor can explain the high variation in heat consumption.

In most cases it is not the same apartments that have high heat consumptions in 2014 as in 2015. In some cases the heat consumption is reduced to the half or even to a fourth from 2014 to 2015 and similarly, increased to the double and even quadruple from 2014 to 2015. This support the findings above and could indicate that either there has been a change of tenant, a change in the number of users in the apartment, or a significant change in the use of the apartment over the two years, e.g. caused by a parental leave or similar. All in all this leads to the assumption that the high heat consumptions and variations in these are not (primarily) related to building physics or orientation but may possibly be related to the user composition or user behavior.

The questionnaire survey can first of all offer an insight into what characterizes this particular user group. The responses show that in 90% of the apartments there are two residents, in 8% only one resident, and in 2% (one out of the 47 submitted responses) there are three residents. Out of the 47 responses two reply that they have a child living in the apartment (corresponding to 4%). The responses show that far the majority of the residents are between 22 and 27 years old (approx. 83%), the youngest resident is 21 and the oldest 34 years old. Hence, the user group is quite homogeneous when it comes to user composition as well as age. Since 9 out of 10 apartments have two residents nor does the number of inhabitants seem to be able to explain the variation in the heat consumption. It cannot, however, be excluded that the number of inhabitants in the apartment can be a contributing explanation of the 9% with highest heat consumptions, as the number of

persons in the household is relatively more important for the heat demand in low energy buildings (Jensen et al. 2011).

In order to get a better understanding of where the inhabitants put their consumption in general – at home or out in the city – it could be interesting to look deeper into how much time they spend in their apartments. The questionnaire survey tells us that on an average weekday, 19 out of 47 respondents (40%) spend 15-19 hours a day in their apartment, 24 respondents (51%) spend 10-14 hours there and 3 (approx. 6%) are home for 9 hours or less. On an average weekend day, 24 respondents (51%) spend 15-19 hours and 10 (21%) spend 20-24 hours in the apartment. Hence, it seems quite characteristic to this user group that the majority spend relatively much time in their apartment. The responses furthermore show that little more than two third have periods of minimum one week where no one lives in the apartment. From the supplementary comments it appears that several of the inhabitants are away from home in more than a few weeks during the year, some up to 5 and 6 weeks. Generally, they leave their apartment in connection with holidays, i.e. over Christmas and New Year's, for winter break (usually in February), Easter and summer break (usually within the period July – August). The heating season in Denmark is typically from October to April, both included, and the fact that some inhabitants leave their home for weeks in this period and others do not, might be part of the explanation for the variation in heat consumptions of the apartments.

Another explanation for the variation might be found in the habitants' practice and habits in regard to ensuring thermal comfort. The thermostat valve stands at 3 by default, which in most cases provides a room temperature at 21 degrees Celsius. The responses show that 30 out of 44 respondents (68%) typically set the thermostat valve lower than 3 in the bedroom, 5 out of 44 (11%) set it on 3 and 2 out of 44 (5%) higher than 3. 7 respondents out of 44 (16%) answer "don't know". For the living room 20 out of 45 respondents (44%) typically set the thermostat lower than 3, 15 out of 45 (33%) on 3 and 5 out of 45 (11%) higher than 3. 5 of the respondents (11%) answer "don't know". In the supplementary comments several respondents moreover note that in fact heating is never on in their apartment. The latter correspond well with the measurements, according to which 20 apartments had no heat consumption at all in 2015. The respondents who never have heat on in their apartment might be among the respondents who answered "don't know", since the questionnaire did not include the option "heat is never on" to this question. The variation in the setting of the thermostat is supported by the responses which state that 27 out of 47 respondents (57%) wish to have different temperatures in the different rooms. When asked how they act to ensure the temperature difference (the respondents could choose more than one options for which reason the sum is not 100%), 26 out of 38 respondents (68%) reply that they close the door between the rooms, 20 out of 38 (53%) open the window to air out before bedtime, 18 respondents out of 38 (47%) adjust the temperature by the thermostat valve and 12 out of 38 (32%) sleep with an open window. Add to this that 31 out of 47 (66%) respond that they turn off the heating if they open a window for more than 5 minutes, whereas 14 out of 47 (30%) do not turn off the heating. When asked about what they do if they find that it is too warm in the apartment (the respondents could choose more than one option for which reason the sum is not 100%), 40 out of 47 respondents (85%) respond that they open a window, 32 (68%) answer that they turn down the heat and only 3 respondents (6%) boost the mechanical ventilation. From the supplementary comments it also appears (again) that several do not have heat turned on at all. A respondent furthermore mentions that he/she wears less clothes when it is too warm.

A similar passive strategy is applied in cases when it gets too cold. 42 out of 47 respondents (90%) reply that they put on a sweater or socks if they find it too cold, whereas 30 out of 47 (64%) note that they turn up the heat.

All in all the responses above indicate that the majority of the inhabitants are quite conscious about how they control the thermal environment in the apartment without wasting energy. The majority turns off the heat when venting and many also seem to choose passive means like e.g. closing the door between rooms to ensure different temperatures, wearing more or less clothes to adjust for shorter periods outside thermal comfort, and opening a window to naturally cool down the room. However, there are also inhabitants whose thermostats are set higher than most and a full 30% of the respondents whom do not turn off the heat when opening windows for a longer period. This type of practice, especially if they are combined, might be part of the reason that some of the apartments have heat consumptions much higher than others. Whether this practice has its ground in lack of knowledge, lack of interest or something else entirely is beyond the scope of this paper to determine. However, it indicates that there is potential for further improvements and future studies may clarify how and by which means energy-conscious practices are best communicated to this particular user group.

## Conclusion

The objective of this study has been twofold; to examine to what extend user practice and habits influence the energy consumption for space heating in a newly built zero-energy youth housing complex in Denmark; and to identify representative user characteristics within this specific user group. On the basis of an analysis where measured data on heat consumptions is juxtaposed with drawings of the building and results from a questionnaire, it is found that the variation in heat consumption across the apartments are not primarily related to apartment type, orientation or floor, but rather related to the inhabitants use of their apartment as well as user practices in regard to thermal comfort.

It is not possible to draw absolute conclusions on the profile of the user group, on the basis of the data presented here. However, the study indicates some general characteristics of this particular user group and some general tendencies in their practices related to ensuring comfort as well as some indications of how this seem to impact the energy consumption. A general characteristic of the group is their appreciation of the right location. This is of far more importance than the energy standard of the building, when they choose where to live. The majority spends relatively much time in their apartment, and consider themselves to be generally concerned about saving energy.

The study identifies two sub groups in the otherwise homogeneous group, and these show two different tendencies. The majority of the user group appears to have general interest in energy-saving aspects and energy-conscious practices as regards ensuring thermal comfort which do not result in high space heating consumptions. This sub group, therefore, do not seem to follow the trend that the expected energy savings in low energy houses are absorbed in increased comfort. To the other sub group, on the other hand, energy-related aspects seem relatively unimportant. The study shows that this smaller group seems to have practices in regard to ensuring thermal comfort which may result in unexpected high heat consumption. Hence, this sub group might be an example of the trend of increased comfort expectations in low energy buildings. Whether this approach and practice is caused by lack of knowledge or lack of interest, is, however, unclear. Although the majority of the group has very low heat consumption, the study concludes that there is

potential for further improvements in order to guide the smaller sub group to more energy-saving practices.

## Acknowledgements

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## References

- Bryman, A. (2012) *Social research methods*. Oxford University Press.
- Bygningsreglementet.dk (2017), *Danish Building Regulation 2015* [online] Available at: <http://bygningsreglementet.dk/english/0/40> [Accessed 28.03.2017]
- Gram-Hanssen, K. (2010) Residential heat comfort practices: understanding users. *Building Research & Information*, 38(2), pp. 175–186.
- Gram-Hanssen, K. (2013) Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption? *Energy Efficiency*, vol 6, nr. 3, pp. 447-457.
- Gram-Hanssen, K. (2014) New needs for better understanding of household's energy consumption: Behaviour, lifestyle or practices? *Architectural Engineering and Design Management*, vol 10, nr. 1-2, pp. 91-107.
- Gram-Hanssen, K. (2015) Hverdag i det topisolerede hus. *Råstof*, no. Sommer 2015, pp. 11-13.
- Jensen, R.L., Nørgaard, J., Daniels, O. & Justesen, R.O., (2011) Resultater: bygningsintegreteret energiforsyning. Aalborg Universitet. Institut for Byggeri og Anlæg, Aalborg. DCE Technical Reports, nr. 7
- Larsen, T.S. & Brunsgaard, C. (2010) Komforthusene: udvikling af passivhuskonceptet i en dansk kontekst. In: T.S. Larsen & S. Pedersen (red), *Towards 2020 - Sustainable Cities and Buildings: 3rd Nordic Passive House Conference 2010*. Aalborg, Aalborg Universitetsforlag.
- Steemers, K. & Yun, G. Y. (2009) Household energy consumption: a study of the role of occupants. *Building Research & Information*, 37:5-6, pp. 625-637
- SurveyMonkey (2017) [online] Available at: <https://www.surveymonkey.com/> [Accessed 17.04.2017]
- Teknologisk.dk (2017). *Teknologisk Instituts graddage 2015* [online] Available at: <https://www.teknologisk.dk/ydelses/der-er-udsigt-til-lidt-hoejere-udgifter-til-opvarmning-for-2015/36720?cms.query=graddage+2015> [Accessed 14.04.2017]
- Yin, R.K. (2003) *Case study research : design and methods*. 3<sup>rd</sup> edition, USA, Sage Publications, INC.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Towards benchmarking of HVAC energy in commercial buildings in warm climates

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**Abstract:** Mechanical cooling and ventilating of buildings is responsible for a significant proportion of their energy consumption. In any benchmarking strategy or operational performance assessment for energy efficiency, it is important to consider calculations or correction factors to account for the impacts of external conditions on the cooling load. Many emerging economies have stocks of commercial buildings of which some operate in fully air-conditioned modes and others in mixed-mode, using air conditioning for a significant proportion of the year. In warm climates, these buildings may interact with the external climate in different ways. In detailed analyses of energy consumption in 32 office buildings across Brazil, buildings are categorised according to HVAC system type and energy consumption is calculated end-use. For each building, the statistical relationship between climate and energy consumption is measured, using cooling degree hours. Buildings which are fully air conditioned show large variations in energy consumption, indicating that although they are conditioned to standard temperatures, they face operational challenges. The buildings with mixed-mode operation are shown to have a more even correlation with external conditions even at high temperatures. This result has implications for steady-state building energy models, benchmark development and climate correction calculations for monitoring and verification.

**Keywords:** Benchmarking, Cooling energy consumption, Climate correction, Energy audit

### Introduction

Improving energy efficiency in buildings requires performance benchmarking. Benchmarks can be used to rate and evaluate energy performance, to identify improvement potential or to track performance through time. A benchmark performance level can be based on top-down methodologies including statistical evaluations of building stocks or bottom-up models developed through building physics (Burman et al. 2013; Hong et al. 2013; Borgstein et al. 2016). Current work in performance benchmarking aims to reconcile the difference between these types of models to produce building performance evaluations where physical characteristics can be used to interpret statistical performance data.

For the purposes of energy performance evaluations, the factors affecting energy consumption in buildings can generally be separated into:

- External factors – principally climate but also local factors such as shading;
- Building efficiency – including both the envelope and the building systems;

- Operational efficiency – most buildings are not optimally operated; and
- Service provision – indoor environmental conditions and usage intensity.

### ***Cooling and HVAC energy in warm climates***

In tropical and sub-tropical climates, especially in emerging economies, commercial buildings generally have no space heating systems but space conditioning often remains the largest energy consumer. As external temperatures will often be within comfortable ranges, a building can aim to provide adequate thermal conditions for its occupants through a fully conditioned (AC) approach, a Naturally Ventilated (NV) approach or a Mixed-Mode (MM) approach. These will require distinct design strategies in order to produce efficient, comfortable buildings (CIBSE 2017).

Many bottom-up models for energy performance evaluation will assume constant internal temperatures during operating hours; this is unlikely to be the case in NV or MM buildings. ASHRAE Standard 55-2013 (ANSI/ASHRAE 2013) includes an adaptive comfort model which can be applied to buildings in which the thermal conditions are regulated by the users primarily through the opening and closing of windows. There are models available to evaluate the performance of NV buildings. For example, Rackes et al have carried out extensive modelling to evaluate the impact of building characteristics on energy consumption of NV buildings, specifically identifying the discomfort hours likely in low-rise buildings, principally schools (Rackes et al. 2016). However, there is a challenge in applying the same tools to mixed-mode buildings, which may use both operable windows and air conditioning during the same day, or sometimes simultaneously.

## **Methodology**

### ***Building data***

Simple building information, such as energy bills, typology and floor area, are often used to carry out simple benchmarking exercises or performance evaluations in homogenous building typologies (Borgstein & Lamberts 2014). However, this simplified information does not provide enough detail to be able to carry out effective performance analyses comparing mixed-mode and fully conditioned buildings.

For this evaluation, detailed building information have been collected on 32 commercial buildings in Brazil. These were primarily office buildings, distributed in 14 cities across the country. Each building was subjected to a full energy audit, following ASHRAE Procedures, levels one or two (ASHRAE 2011). The principal building systems and envelope were catalogued and evaluated, a full end-use breakdown was estimated using CIBSE's TM22 methodology (CIBSE 2006) and energy saving measures were listed. Each of the buildings exhibits unique characteristics related to its occupation, systems and operations. Data collection is difficult and requires repeated site visits. Several different definitions of area are used and often these are not clearly defined. Occupancy rates vary significantly throughout the year and record-keeping is not always accurate. Often building managers supplied incomplete or erroneous information, requiring detailed investigation and checking.

### ***Levels of service provision***

The buildings evaluated have different levels of operational and systems efficiency. Several buildings do not meet full requirements for occupant satisfaction, either through underperforming air conditioning systems or low lighting levels. There were also major

differences in building floor area ratios; some had air conditioning installed in less than 50% of the area, others were only partially occupied whilst others were fully occupied and conditioned. Finally, use intensity varied: one building was dominated by a cultural centre, another by a major data centre, others had varying densities of occupation ( $\text{m}^2$  per person). These factors all have major impacts on the total energy consumption.

### **Climate data**

Energy consumption in buildings can be impacted by factors like air temperature, humidity, wind speed, direct solar radiation and cloud cover. These will have different impacts, depending on the type of building, but a meta-model developed by Rackes et al shows that for the commercial buildings studied in warm climates (principally low-rise buildings), the number of cooling degree hours is the single characteristic with the greatest impact on energy consumption of simulated buildings, (Rackes et al. 2016).

The Brazilian Institute of Metrology (INMET) has provided historical climate data for several hundred cities in Brazil, which has been used to produce weather years that are provided online for building performance simulation (LABEEE, n.d.). In addition, some recent data is made freely available by INMET, including air temperature and relative humidity. As dry-bulb air temperature is the dominant climate impact on building energy consumption, cooling degree hours (CDHs) are calculated and used to map climate intensity and evaluate performance. Based on the authors' experience in modelling balance temperatures for buildings in warm climates, 22°C is selected as the base temperature for calculating CDH according to Equation 1.

$$CDH = \sum_{hours} (T - T_{base})^+$$

Equation 1.

T = mean hourly temperature;  $T_{base}$  = base temperature, 22°C

CDHs can be easily calculated for both the weather years used for simulation in Brazil, and the real recent weather conditions in selected cities. In order to use them for performance evaluations, they are calculated and tabulated on a monthly basis.

In general, the term climate normalisation or climate correction is used for comparing energy consumption by buildings in different climatic regions (spatial adjustment), while weather normalisation is used to compare building performance over time in the same region (time adjustment). As described in Table 1 and illustrated in Figure 1, there is a significant difference between the historical weather data provided for some major cities in Brazil, and the actual recent climatic conditions. Although some months are colder than historical data would indicate, the greatest differences appear to be in peak temperatures during hot months. This is likely to be due to a combination of climate change and urban heat islands, leading to more intense climatic events such as heat-waves in the summer. This would seem to clearly indicate the importance of using weather normalisation for building performance evaluation, especially when monthly data are considered. The three-year average CDH is close to the INMET level for Brasília and Belo Horizonte (within 10%), but is 43% and 67% above the INMET level for Rio de Janeiro and São Paulo respectively.

Table 1 – Monthly means of cooling degree hours in selected Brazilian cities

Mean monthly CDH	Rio de Janeiro	São Paulo	Belo Horizonte	Brasília
2014-2016 (3 years)	2427	980	1355	1097
INMET	1694	588	1228	1152

## Climate-related energy consumption

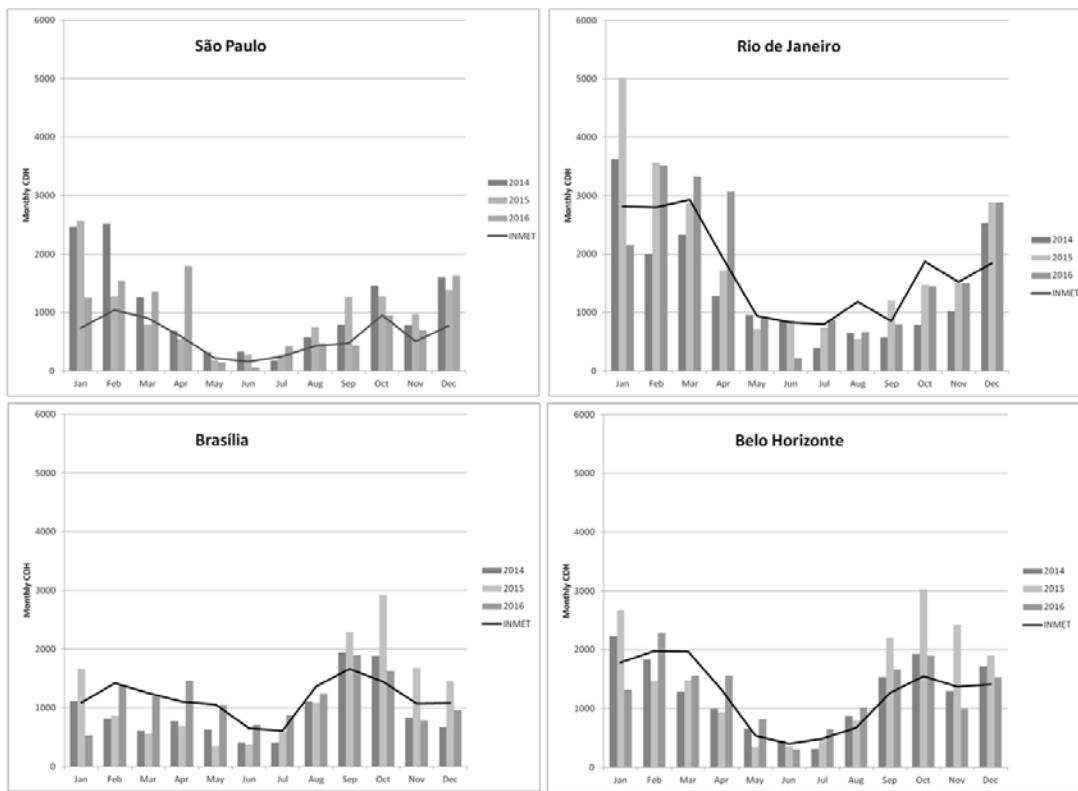


Figure 1. Comparisons of cooling degree hours calculated from historical weather data (INMET) and measured temperature for recent years

In order to carry out evaluations of energy performance related to weather in different building types, it was necessary to clean the data. Firstly, monthly energy consumption was calculated and normalised by the useful floor area. The major end-uses which are not classed as normal building services for offices (usually data centres) were subtracted from total energy consumption, using the mean annual percentage of the energy consumed by these systems. A correction factor was applied for the number of working days per month, to account for some months containing more weekends and national public holidays. Finally, buildings which could not be classified as principally office spaces were removed from the dataset.

The building HVAC systems were described and their primary cooling technology tabulated. In larger buildings, centralised HVAC systems are used to condition a whole building and are generally chilled water systems, although some may be variable refrigerant flow (VRF). Generally, in buildings with centralised systems over 80% of the area is conditioned (stairwells and corridors are usually not conditioned) and these buildings almost always have central control and operation. Distributed HVAC systems nearly always use direct expansion (DX) units, primarily split air conditioners. They may be fully conditioned or may only have air conditioning installed in a small proportion of the building, but the air conditioning is operated locally and does not have a central control system. Separately, the buildings were evaluated according to their window operation. By noting whether the majority of windows were operable, the number of windows open during the visits and the use of windows cited in interviews with building managers, buildings were classified as having fixed or operable windows.

With few exceptions, smaller buildings had operable windows and distributed HVAC systems and were considered Mixed-Mode (MM), while larger buildings had fixed windows

and centralised HVAC systems and were considered Fully Conditioned (AC). One smaller building had a DX system but did not have operable windows, so was classified AC, while one large building classed as MM – it did not have a central air conditioning system because it was built before such systems were available.

## Results

The energy consumption for the 32 buildings in the dataset was broken down five end-use groups: HVAC, lighting, plug loads, data centres and other. The division of the energy consumption according to these categories is shown in Figure 2 for the MM buildings in the dataset (14 buildings) and in Figure 3 for the AC buildings (18 buildings). This data is not normalised for occupancy density or for climate, but it is clear that AC buildings generally have a larger consumption for HVAC, while data centres can cause significant distortions of the results.

The energy disaggregation provided for the buildings during the energy audits is based on estimated or calculated data, generally using a few spot measurements to calibrate estimates. As such, the end-use data was not deemed accurate enough to separate cooling energy consumption for an isolated analysis. Instead, the removal of major distortions from data centres and non-standard energy uses left a more uniform basis for comparison, based on standard building services (cooling, ventilation, heating, plug loads, lighting, elevators and UPS systems). Although no correction was made for occupant density, the vacancy rates were considered in the calculation (consumption was normalised by occupied area), and operational hours were found to be similar in all the buildings.

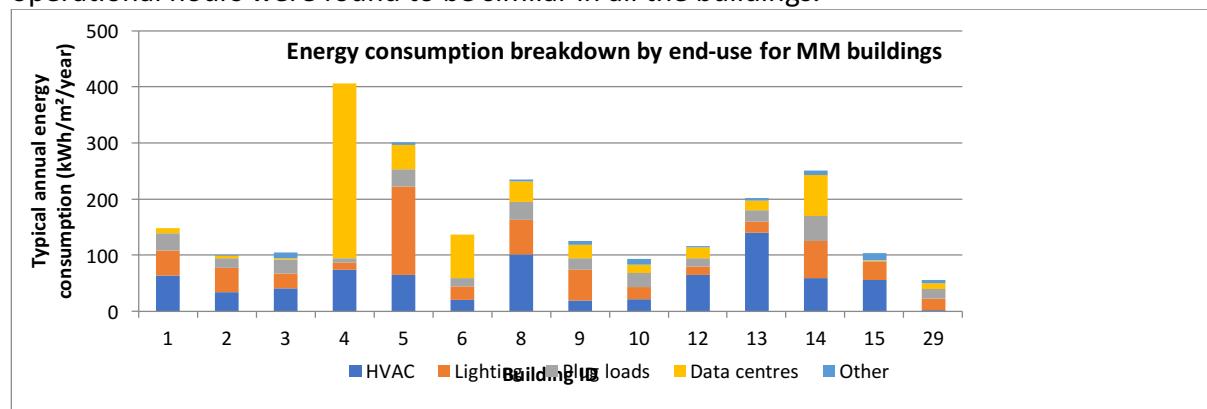


Figure 2. Energy consumption in five major end-use categories, calculated for mixed-mode buildings

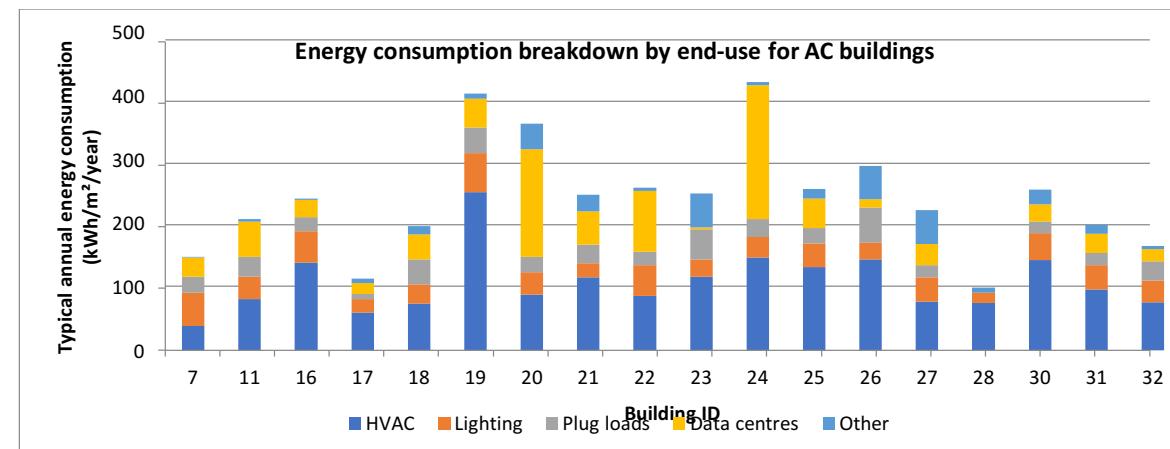


Figure 3. Energy consumption in five major end-use categories, calculated for fully conditioned buildings

The corrected monthly energy consumption for each building was then paired with the monthly degree days calculated for the month in which the energy consumption took place. Buildings 4 and 23 were excluded and there were between 12 and 24 energy bills available for each building, producing a total of 617 data points (292 in MM buildings and 325 in AC buildings).

Figure 4 shows the energy consumption of mixed-mode and air-conditioned buildings, plotted against the energy consumption of the relevant month. A linear, least-squares regression between degree days and energy consumption gave a positive correlation for each building individually, with one exception (this AC building was undergoing retro-commissioning at the time when the data were collected). However, there is clearly a large variation between buildings and the statistical relationships were generally weak. Overall, the AC buildings demonstrate higher energy consumption and greater variability, as well as a slightly higher energy consumption increase in higher temperatures. A further evaluation was carried out on the MM buildings, removing the buildings which had in which the conditioned area was below 50% of the total useful area, as these buildings would be expected to show different relationships with temperature. The scatter-plot in Figure 5 shows the results in the ten remaining buildings, with a linear least-squares regression. Although the  $R^2$  value is still only 35%, this plot shows a clearer statistical relationship between energy and temperature.

The higher energy consumption of AC buildings is to be expected, as fully conditioned buildings are generally expected to provide a higher level of service: constant year-round temperatures, air filtration, barriers to noise pollution and low air speeds, for example. Several of the buildings in this study were considered AAA-level corporate offices, which may also have higher equipment densities due to the use of UPSs and tasks which are more computer-intensive. Several of the AC buildings had undergone sustainability certifications at the time of construction, which requires the inclusion of high-efficiency equipment to meet international certification parameters (Brazilian legislation does not currently include any energy efficiency requirements for commercial buildings). Although these buildings showed less variation than other buildings in the AC dataset, they still demonstrate higher energy consumption than MM buildings. In general, the high variation and low predictability of performance amongst the AC buildings is likely to be related to their use of larger, more complex equipment for building conditioning. Although this equipment can be designed and operated in a highly efficient fashion, the data from the energy audits showed that HVAC equipment was never operating under optimal conditions and, in some cases, was responsible for sharply increased energy consumption because of incorrect operational parameters. The lack of professional commissioning, poor maintenance, the low level of expertise of building managers and a lack of strategic oversight or energy management are responsible for this variation.

In MM buildings, there was also a significant variation in energy performance, with some buildings showing characteristics that were far from typical. However, there was a greater degree of standardisation of equipment and operation: air conditioning was provided through split or window units and building occupants could operate windows as and when required. Four of these buildings were only partially conditioned, and once these were removed from the dataset, there was a high degree of correlation between energy consumption and climate.

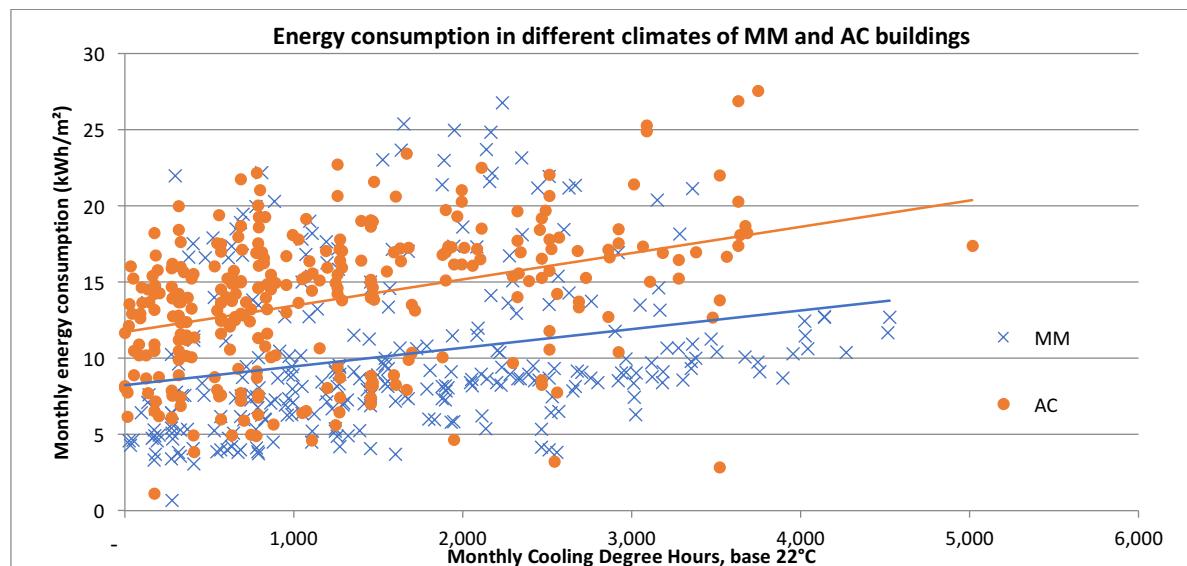


Figure 4. Energy consumption versus CDH in mixed-mode and fully conditioned buildings (30 buildings, data centre energy consumption excluded)

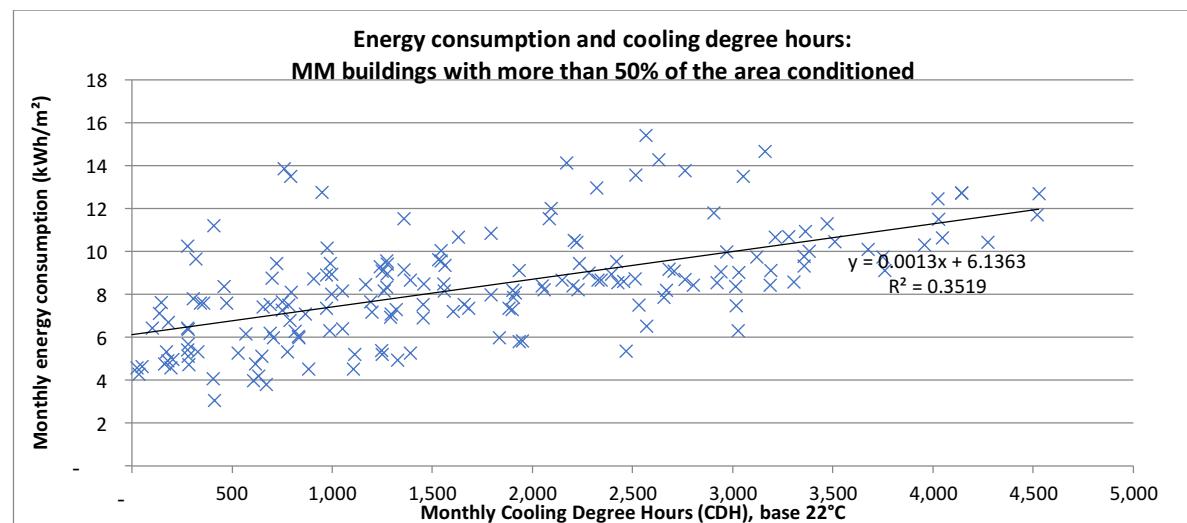


Figure 5 - Energy consumption versus temperature for mixed-mode (MM) buildings in which the majority of the area is conditioned (8 buildings, data centre energy consumption excluded)

## Discussion

Although some AC buildings show performance levels equivalent to MM buildings, most have higher energy consumption. Excluding data centres, the mean annual energy consumption of MM buildings was 124 kWh/m<sup>2</sup>/year and only three of the 18 AC buildings had energy consumption below this level; the mean for MM buildings was 188 kWh/m<sup>2</sup>/year. As AC buildings tend to have more complex systems, with efficient chillers or VRF units, they might be expected to demonstrate better levels of efficiency at higher temperatures, where their systems would be fully utilised. Following this logic, MM buildings would have higher energy consumption at high temperatures due to their low efficiency, while external temperatures would be too high to allow windows to be opened. However, this is not demonstrated in the results, which instead show that the energy consumption of AC buildings increases with temperature at a faster rate than that of MM buildings. Reasons are likely to involve poor operational practice, lack of design optimisation, higher internal loads and some levels of discomfort at high temperatures in MM buildings.

The adaptive comfort model from ASHRAE 55-2013 would indicate that MM buildings can operate in a wider range of temperatures; the results of this paper seem to indicate that the impacts on energy consumption of the wider comfort range are measurable and significant. Clearly, there are several other factors with significant impact on energy consumption that were not considered here. Amongst external factors, levels of wind speed, solar radiation, humidity and external shading were not considered. The simple normalisation carried out made no attempt to correct for levels of occupant density, systems efficiency and operational efficiency; these three factors are likely to account for a significant proportion of the remaining variation in building energy consumption.

These results indicate several areas for further research. Additional weather variables (beyond CDH) should be tested to find out which, if any, will be required for benchmarking climate-related energy consumption. With a weather correction factor applied, further development of analytical tools to separate the energy consumption due to operational inefficiency and systems efficiency should be carried out, to show the performance improvement potential for an individual building.

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## List of abbreviations

CDH – Cooling Degree Hours, considering dry-bulb temperatures with base 22°C unless otherwise specified  
MM – Mixed-mode building, which can operate using air conditioning and/or operable windows  
AC – Air conditioned building, does not typically operate opening windows in the majority of the usable area  
NV – Naturally ventilated building, which has little or no air conditioning.  
INMET – Brazilian Institute for Metrology, which publishes weather data from across the country.  
DX – Direct expansion air conditioning system (typically includes split and window systems)  
UPS – Uninterruptible Power Supply

## References

- ANSI/ASHRAE, 2013. Standard 55-2013 - Thermal environmental conditions for human occupancy
- ASHRAE, 2011. Procedures for Commercial Building Energy Energy Audits
- Borgstein, E.H. & Lamberts, R., 2014. Developing energy consumption benchmarks for buildings: Bank branches in Brazil. *Energy and Buildings*, 82, pp.82–91.
- Borgstein, E.H., Lamberts, R. & Hensen, J.L.M., 2016. Evaluating energy performance in non-domestic buildings: A review. *Energy and Buildings*, 128, pp.734-755.
- Burman, E. et al., 2013. A comparative study of benchmarking approaches for non-domestic buildings: Part 2 - Bottom-up approach. *International Journal of Sustainable Built Environment*, 2(2), pp.119–130.
- CIBSE (2017) Designing for Extreme Environments: Tropical, Chartered Institute of Building Services Engineers.
- CIBSE, 2006. TM22 : Energy assessment and reporting method,
- Hong, S.-M. et al., 2013. A comparative study of benchmarking approaches for non-domestic buildings: Part 1 – Top-down approach. *International Journal of Sustainable Built Environment*, 2(2), pp.119–130.
- LABEEE, Weather data for EnergyPlus simulations, [www.labeee.ufsc.br](http://www.labeee.ufsc.br) (accessed 04/04/2017)
- Rackes, A., Melo, A.P. & Lamberts, R., 2016. Naturally comfortable and sustainable: Informed design guidance and performance labeling for passive commercial buildings in hot climates. *Applied Energy*, 174, pp.256–274.



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*Design to Thrive*

## Can Activity-Based Working spaces increase worker's physical activity, perceived productivity and satisfaction?

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**Abstract:** A lot of effort has been devoted recently to investigating if a new breed of 'active design', where occupants are no longer develop their activities at a single fixed-location, can actually help increasing physical activity. This trend in workspace design is known as Activity-Based Working. Despite all the best efforts made this far when trying to understand positive and negative aspects of different workspace layouts on occupants' physical activity, a knowledge gap remains when it comes to detailed investigations focusing on ABW settings. This is particularly true in Australia where the uptake of ABW has plumped in recent years. This paper presents results from a case study, aimed quantifying workers' physical activity before and after relocation from a contemporary open plan office to an ABW setting. This paper also discusses occupants' perceived productivity and overall satisfaction before and after relocation. A total of 89 volunteers participated on the occupancy survey and 20 during the physical activity monitoring. Wearable devices were used to monitor step count and physical activity for two weeks during the pre-evaluation (contemporary open plan office) and post-evaluation survey (ABW). After moving to an ABW layout occupants were slightly more active than before, walking 0.2km more on average daily. A significant reduction of 6% in sedentary time was also observed with an increase of 20% on active time. Post-occupancy results also indicated a significant increase on perceived productivity and consistent improvements on occupants' satisfaction on all IEQ variables. These preliminary results suggest that active workspace design may have a positive impact on workers' physical activity, perceived productivity and satisfaction and should therefore be more investigated.

**Keywords:** Indoor Environmental Quality (IEQ), Post-Occupancy Evaluation (POE), workspace design, green buildings.

### Introduction

Sustained sitting has colloquially been termed 'the new smoking' and with millions of people spending most of their time at work, there is plenty of evidence indicating the workplace as central to public health. A large-scale study focusing on contemporary workspace in the UK has found that office workers demonstrated high levels of sitting during the working week (approximate 10.6 hours per day) (Smith et al 2015). Recent Australian research has linked excessive sitting to an increased risk of chronic disease-related morbidity and mortality (Thorp et al 2011). Awareness about the benefits of moving more and sitting less during the day can be exemplified by the 10,000 steps/day campaigns and trend in use growing popularity of sit-stand desks.

Activity Based Working (ABW) includes changes on organizations' culture and space configuration and it is based on two key points: (i) non-individual territoriality, and (ii) a

variety of spaces purposively designed to accommodate different tasks. The implementation of these points varies largely from organization to organization and there is agreement that tailoring is needed for successful implementation. The ABW configuration of office space fits into the active design trend framework it may enable incidental physical activity opportunities and workers' movement may occur more frequently (Active Design Guidelines, 2010).

Despite all the best efforts made this far when trying to understand positive and negative aspects of different workspace layouts on occupants' physical activity, a knowledge gap remains when it comes to detailed investigations focusing on ABW settings. This is particularly true in Australia where the uptake of ABW has plumped in recent years. Preliminary results from a pre-post evaluation study found a 14% reduction in daily sitting time, partially compensated for by increases in standing (10%) and stepping time (2%) in occupants from a large company after moving into an ABW fit-out (Foley et al 2016). Significant differences were also found by Engelen et al (2017) before and after relocation to an active space with regards to the time workers spent seated (72%-66) and standing (15%-19) but walking remained unchanged.

With at least 10 million workers spending most of their time in their workplace (Heart Foundation, 2012), and the penetration of ABW in the property market getting higher, the opportunity cost of lack of studies to understand this new way of working is simply too high to be ignored. This paper presents results from a case study, aimed quantifying workers' physical activity before and after relocation from a contemporary open plan office to an ABW setting. This paper also discusses occupants' perceived productivity and overall satisfaction from Post-Occupancy Evaluation (POE) surveys conducted before and after relocation.

## Methodology

A total of 89 office workers from the same organization were relocated from a combi office into an Activity-Based Working setting. All workers were invited to participate on the pre and post POE surveys and a subset of 20 volunteered to contribute to the physical activity monitoring. The post survey was conducted six months after relocation to the new premise.

The old fit-out featured two open-plan offices with a combi typology. Occupants worked from the same workstation and used shared facilities, including meeting rooms of various sizes. The new ABW fit-out adopts active design principles and introduced spaces for breaks and more zones allocated for supporting collaboration and concentration. Physical environments are flexible and workers' mobility is enabled by technology. The new office also features a multi-purpose space designed to support a variety of activities, including mindfulness sessions, events, collaboration and breaks. All workstations are sit/stand and workers are required to work from different locations every day. Clean desk policy, lockers, end of trip facilities and portable keyboards were also implemented. There was a strong engagement process before and after relocation. All buildings surveyed have air-conditioning system and fit-outs are relatively new or had some sort of refurbishment done less than 5 years before the study was conducted. Personal control systems are non-existing. Table 1 shows demographic data for surveyed buildings.

The study presented here used the Building Occupants Survey System Australia (BOSSA) Time-Lapse questionnaire for the purposes of pre and post surveys. BOSSA is an IEQ assessment system for office buildings. Details about the project and methodology can be found on Candido et al (2016). The BOSSA Time-Lapse questionnaire includes background

questions addressing participants' gender, age, type of work, time spent in buildings, workspace arrangement and modules focusing on spatial comfort, individual space, indoor air quality, thermal comfort, noise distraction and privacy, visual comfort, personal control, building image and overall occupant satisfaction. Workers rate their satisfaction on a seven-point scale (1 = the lowest rating; 4 = neutral and 7 = the highest rating). In addition to the survey, floor plans and building metrics information (including base building and fit-out information) are also collected. Combined, this information is a unique feature of the BOSSA POE tool and it has been helping researchers to contextualize occupant survey responses. For the purposes of this paper, a total of 97 BOSSA Time-Lapse questionnaires were analyzed - 41 responses came from pre-evaluation surveys and a subsequent 56 sample from post-evaluation.

Table 1. Demographic data for surveyed buildings, including pre and post relocation.

	Combi (n = 41)	ABW (n = 56)
Tenant Net Lettable Area	940	1234
Gender		
<i>Female</i>	26.8%	23.2%
<i>Male</i>	73.2%	76.8%
Age		
<i>30 years old or under</i>	17%	29%
<i>31 to 50 years old</i>	68%	54%
<i>Over 50 years old</i>	15%	18%
Type of work		
<i>Administrative</i>	17%	13%
<i>Technical</i>	27%	21%
<i>Professional</i>	44%	52%
<i>Managerial</i>	12%	11%
<i>Other</i>	0%	4%

Wrist-worn devices were used to monitor step count and physical activity for two weeks during the pre-evaluation and post-evaluation surveys. Weekends, public holidays and the shutdown period over Christmas were excluded. Only the data from the participants who provided data in both pre and post occupancy periods were used – some people left the organization before the post-occupancy stage.

## Results

Results from Figure 1 indicate that building occupants reported higher satisfaction on Indoor Environmental Quality conditions of the new workspace. Mean score results from the BOSSA Time-Lapse survey on thermal comfort (summer and winter), acoustics (interruptions, sound privacy and overall noise), Indoor Air Quality, lighting/access to daylight and the degree of freedom to adapt their work area were significantly higher on ABW configuration. These results were consistent to findings from comparative analysis conducted on the entire BOSSA database (Candido et al, 2016, 2017) and differ from previous findings from De Been and Beijer (2014).

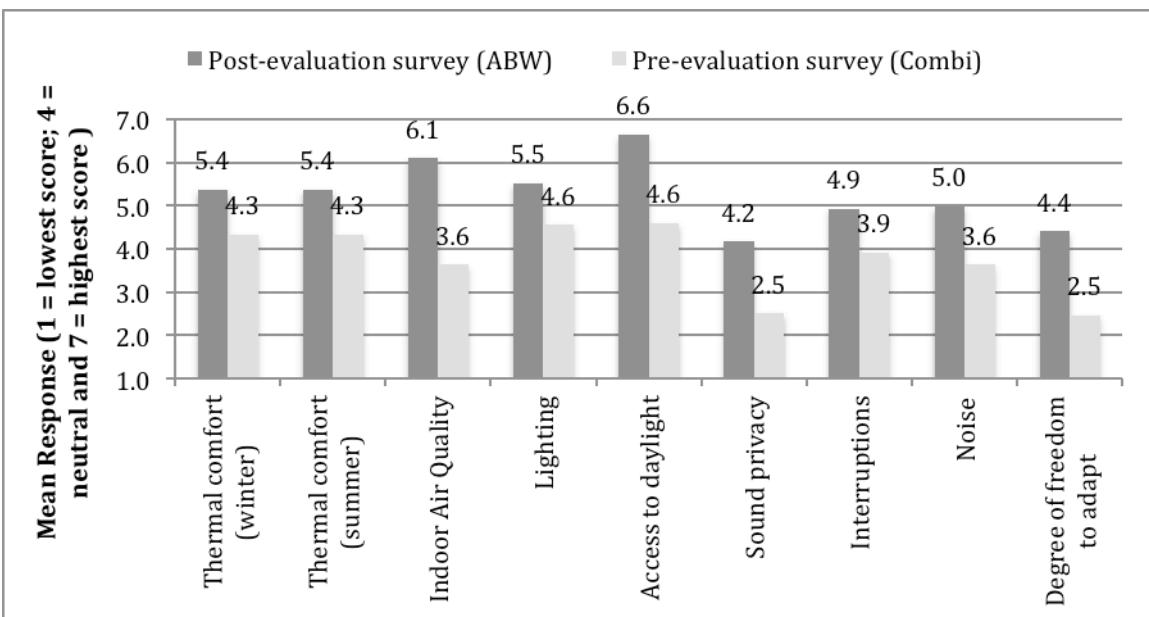


Figure 1. Break down of BOSSA Time-Lapse survey results on thermal comfort, Indoor Quality, visual comfort and acoustics.

Interestingly, when it comes to acoustics, sound privacy and distraction/unwanted interruptions – a critical issue of open-plan offices, workers reported higher satisfaction in the new ABW office. This may due to the implementation of spaces for concentration, private conversations and phone calls in ABW layouts, which did not exist on the combi layout. The overall openness of the floor plan of the new office and the layout that facilitates access to daylight and views may justify occupants' perception of lighting and daylight. Another possibility is the flexibility to work from workstations by the building façade, which is a feature of the new office configuration. The ability to move around the workspace may in turn give workers more choice. This may justify the significantly higher satisfaction results on the degree of freedom to adapt their work area question noted post-relocation.

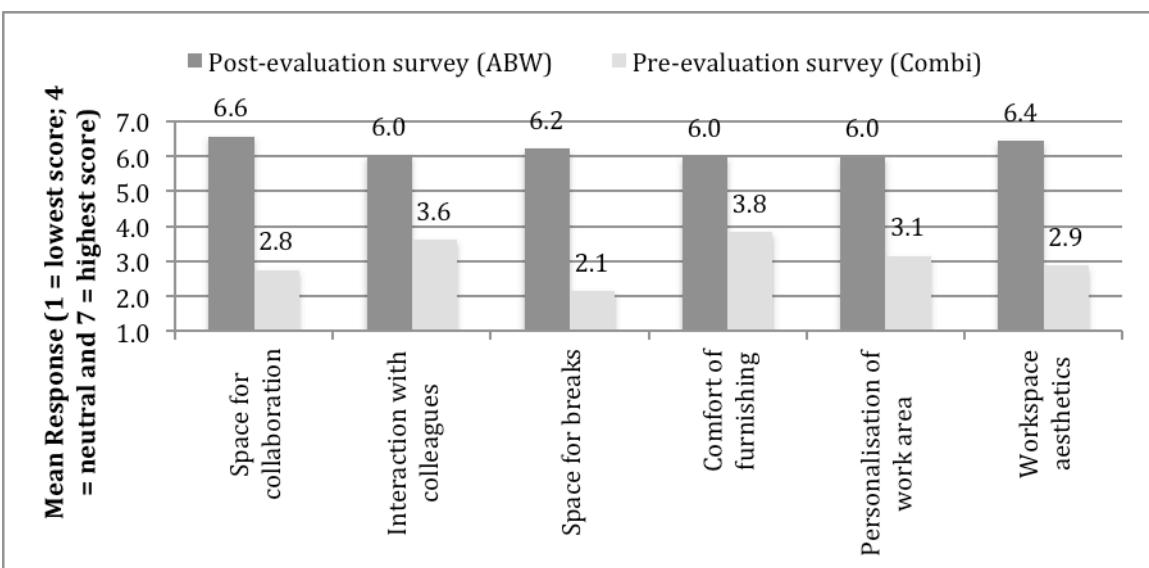


Figure 2. Break down of BOSSA Time-Lapse survey results on Spatial Comfort module's questions.

One of the main drivers of the relocation was collaboration and the motivation to align the new fit-out with the values and culture of the organization. Figure 2 illustrates result from the BOSSA's Spatial Comfort module. Combined, these results from all questions in this module suggest that workers' were orders of magnitude more satisfied with the new workspace. Satisfaction scores on space for collaboration and interaction with colleagues question more than doubled after relocation to the ABW space. Satisfaction with space for breaks tripled in the new office.

Active design features have the potential to promote health and increase incidental physical activities opportunities. The results post-relocation suggest that such the ABW configuration may have some positive impact on worker's overall step count and reduced occupational seating. After relocation to the ABW workspace, occupants were slightly more active than before, increasing their walking by 0.2km on average, daily. Results from Figure 3 show step-count data before and after relocation. A significant reduction of 6% in sedentary time was also observed with an increase of 20% on active time overall. These results are consistent with case studies in the literature showing increase on overall physical activity (Engelen et al, 2017) and reduction on sedentary time (Foley, et al, 2016).

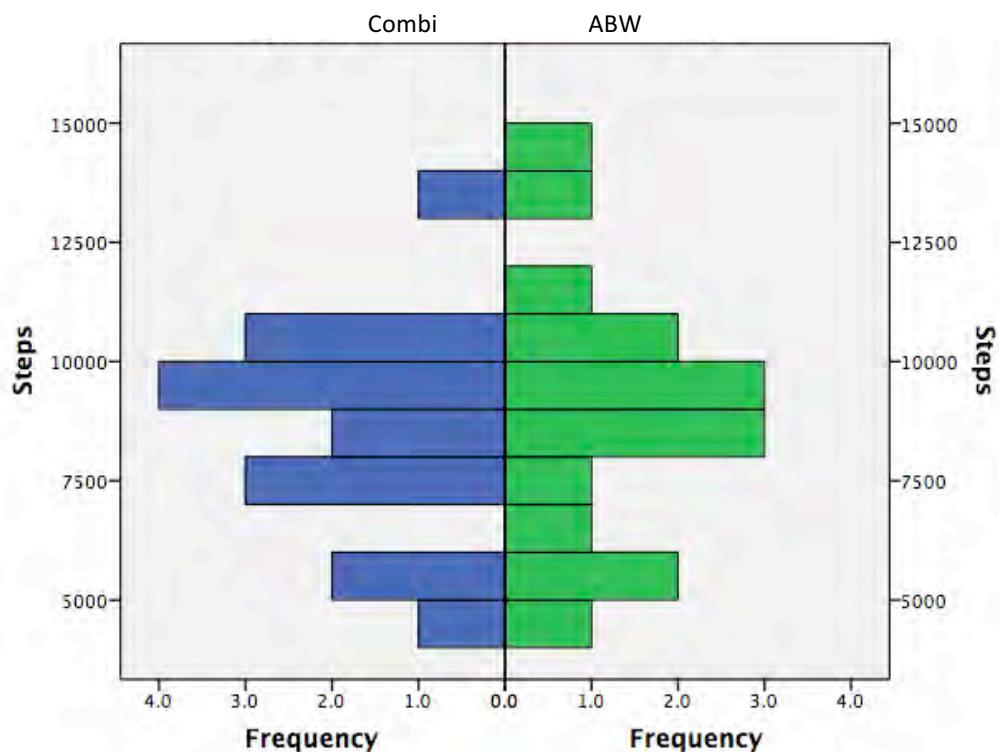


Figure 3. Step-count distribution before and after relocation.

BOSSA POE results after relocation also indicate that office workers' satisfaction were significantly higher than pre-evaluation surveys on overall comfort, overall building, perceived productivity and health questions. Figure 4 depicts these results. These findings agree with previous studies - employees in ABW environments reported better health than employees in combi offices (Vischer, 2005; Bodin, Danielsson and Bodin, 2008).

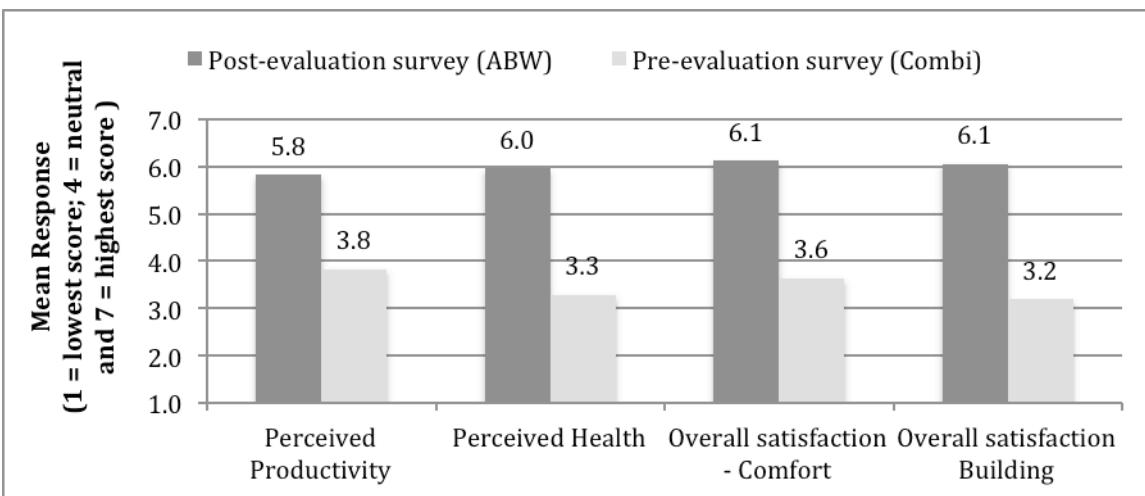


Figure 4. Break down of BOSSA Time-Lapse survey results on workers' overall satisfaction with the comfort of their work area, building as well as perceived productivity and health.

## Conclusions

This paper presented case study results from Post-Occupancy Evaluation (POE) and step count monitoring from office workers relocated from a contemporary open-plan office setting (pre evaluation) into an ABW layout (post-evaluation). After moving to an ABW layout occupants were slightly more active than before and a significant reduction in sedentary time was also observed. Post-occupancy results also indicated a significant increase on perceived productivity and consistent improvements on occupants' satisfaction on all IEQ variables. Although limited, these preliminary results suggest that active workspace design may have a positive impact on workers' physical activity, perceived productivity and satisfaction and should therefore be more investigated. These results may serve as an indicator to designers, tenants and buildings owners about ABW settings while at the same time contributing to a knowledge gap observed in academia in Australia.

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## References

- Active Design Guidelines. (2010) NYC. <http://centerforactive-design.org/guidelines/>
- Bodin Danielsson, C., & Bodin, L. (2008). Office type in relation to health, well-being, and job satisfaction among employees. *Environment and Behavior*, 40(5), pp. 636-668.
- Candido, C. M., Kim, J., de Dear, R., Thomas, L. (2016). BOSSA: A multidimensional Post-Occupancy Evaluation tool. *Building Research and Information* (Print). v.44(2), p. 214-228.
- Candido, C., Zhang, F., Kim, J., de Dear, R., Thomas, L., Joko, C., Strapasson, P. (2016). Impact of workspace layout on occupant satisfaction, perceived health and productivity. In: Proceedings of 9th Windsor Conference: Making Comfort Relevant. Cumberland Lodge, Windsor, UK, 7-10 April 2016.

Candido, C. and Zhang, F. (2017) Workers' satisfaction in contemporary open-plan offices: a case-study comparison in Australian premium workspaces. In: 24th Conference of the European Real Estate Society, June 28 - July 1, 2017, Delft.

Chau, J.Y., Sukala, W., Fedel, K., Do, A., Engelen, L., Kingham, M., Sainsbury, A., Bauman, A.E. (2016) More standing and just as productive: Effects of a sit-stand desk intervention on call center workers' sitting, standing, and productivity at work in the Opt to Stand pilot study. Preventive Medicine Reports, 3, pp. 68-74.

De Been, I., Beijer, M. (2014). The influence of office type on satisfaction and perceived productivity support, Journal of Facilities Management, Vol. 12 Iss 2 pp. 142-157.

De Croon, E., Sluiter, J., Kuijer, P.P. and Frings-Dresen, M. (2005). The effect of office concepts on worker health and performance: a systematic review of the literature, Ergonomics, Vol. 48 No. 2, pp. 119-134.

De Paoli, D., Arge, K., Blakstad, S.H. (2013). Creating business value with open space ABW offices, Journal of Corporate Real Estate, Vol. 15 Iss 3/4 pp. 181-193.

Engelen, L., Dhillon, H.M., Chau, J.Y., Hespe, D., Bauman, A.E. (2016). Do active design buildings change health behaviour and workplace perceptions? Occupational Medicine, 66 (5), pp. 408-411.

Engelen, L., Chau, J., Bohn-Goldbaum, E., Young, S., Hespe, D., Bauman, A. (2017) Is Active Design changing the workplace? - A natural pre-post experiment looking at health behaviour and workplace perceptions Work, 56 (2), pp. 229-237.

Foley, B., Engelen, L., Gale, J., Bauman, A., MacKey, M. Sedentary Behavior and Musculoskeletal Discomfort Are Reduced When Office Workers Trial an Activity-Based Work Environment (2016) Journal of Occupational and Environmental Medicine, 58 (9), pp. 924-931.

Heerwagen, J.H., Kampschroer, K., Powell, K.M. and Loftness, V. (2004). Collaborative knowledge work environments, Building Research & Information, Vol. 32 No. 6, pp. 510-528.

Medibank. (2011). Sick at work. The cost of presenteeism to your business and the community. Medibank Research Series, 1-12.

Penn, A., Desyllas, J. and Vaughan, L. (1999). The space of innovation: interaction and communication in the work environment, Environment and Planning B: Planning and Design, Vol. 26, pp. 193-218.

Vischer, J.C. (2005). Space Meets Status: Designing Workplace Performance, Routledge, London.

WGBCA (2012). Health, Wellbeing & Productivity in Offices. The next chapter for green building. pp 1 - 87.



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*Design to Thrive*

## Indoor Environmental Quality conditions in Activity-Based offices in green buildings

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**Abstract:** Activity-Based Working (ABW) is a trend in contemporary workspace design that encourages building occupants to work at different areas of the workspace depending on the nature of their activity. As a result, the physical environment hosts a myriad of spaces dedicated to collaboration, concentration, private conversations, socialization, etc. The adoption of this typology has increased significantly in Australia, however empirical evidence on the performance of such workspaces is scarce. Considering that ABW environments are normally more densely occupied and different zones may have distinct microclimates due to the layout and activity developed by occupants, there is a need to properly understand the Indoor Environmental Quality (IEQ) conditions in these workspaces. This paper compares monitored IEQ conditions of ten contemporary open-plan workspaces with ABW or combi layouts. Workspaces are located within green certified buildings in Australia that are of similar age, fully air-conditioned by a VAV system and hold an energy certification. Spot measurements of thermal comfort, acoustics, lighting and air quality were taken in the morning and afternoon. Readings were averaged for 15 minutes for each point and a total of 5 points per floor were monitored in each workspace, including one for each façade, interior and perimeter zones. Results indicate that combi offices were slightly warmer, had lower air speed values and were slightly less humid than ABW. Indoor Air Quality readings were similar in both settings. Higher illuminance was observed in ABW offices. Not surprisingly, considering the open plan nature observed in both layouts, there were no significant differences for sound pressure levels. Although within recommended thresholds, these results suggest the need to properly consider and adapt layouts and building features when designing Activity-Based Working environments.

**Keywords:** Indoor Environmental Quality (IEQ), Post-Occupancy Evaluation (POE), workspace design, green buildings.

### Introduction

Recently, there was an increase on the number of organizations joining the New Ways of Working (NWoW) trend in the Australian property market. Organizations are willing to pay premium for office premises specifically designed to accommodate Activity-Based Working (ABW). A polarizing topic in industry, ABW is a way of working that requires building occupants to move and work from different areas of the office, depending on the nature of the task – work is essentially understood as an activity and as such, it should not be confined to a place. As a result, the physical environment supporting ABW features a variety

of spaces dedicated to collaboration, concentration, private conversations, socialization, etc. In Australia, such environments have been embraced by organizations occupying premium-upgraded, certified building premises. Organizations have increasingly been using the workspaces designed to support ABW as a key component of their business' brand, values, culture and subsequently talent attraction and retention (Vischer, 2005).

Direct financial benefits from the reduced-office footprint (and consequently rent) may continue to be one of the key drivers behind the ABW uptake, but this narrow view has been replaced by discussions around indirect gains from increased collaboration, incidental physical activity opportunities, perceived productivity and wellbeing (De Been and Beijer, 2014, Bruria et al, 2016, Candido et al 2017, Engelen et al, 2016, Engelen et al, 2017). Despite its growth in popularity in Australia, empirical evidence on the performance of such workspaces is yet to follow suit.

If we look into the physical aspects of workspace, ABW environments may be more densely occupied because of a reduced office footprint when compared to contemporary open-plan offices, and different zones may present distinct microclimates due to the layout and activity developed by occupants. When combined, these two characteristics may influence the Indoor Environmental Quality (IEQ) conditions workers are exposed to. Considering the estimations around the affect of IEQ on workers' perceived productivity, there is a need to properly understand these workspaces (Appel-Meulenbroek et al, 2016, Bruria et al, 2016) and the timing in right – recently, many Australian organizations have embraced pre-and-post evaluation surveys largely motived by requirements from the Green Building Council of Australia's Green Star-Performance tool. As a result, the property market is now being populated with potential case study-comparisons.

Recent results from case studies conducted in premium-certified ABW offices in Australia, suggest that workers occupying ABW settings were significantly higher satisfied with spatial comfort, Indoor Air Quality, thermal comfort, visual comfort and acoustics (Candido et al, 2016). Results also suggest that workers reported significantly higher satisfaction on overall comfort, overall building, perceived productivity and health questions (Candido et al, 2017). Ironically, the lack of ownership, may be a positive feature of ABW environments – by being constantly "on the move", workers' may have more freedom to find zones that may suit their individual preferences. This paper adds to this research by comparing monitored IEQ conditions of ten workspaces with ABW or contemporary open-plan layouts (combi) located in green-certified buildings.

## **Methodology**

All ten workspaces are located within green certified buildings in Australia. They are of similar age, fully air-conditioned by a VAV system and hold an energy certification. The size of the floor plan ranged from 1,291 to 65,664m<sup>2</sup>. Table 1 shows basic information about buildings included during the IEQ monitoring period.

Floor plans analyses show that contemporary open-plan premises presented a layout typology of an ABW or combi office (De Been and Beijer, 2014). All six combi offices present a mix of open and enclosed spaces of various sizes plus meeting rooms and shared facilities. Workers are assigned to a desk and they work from the same location. All four Activity-Based Working offices present a variety of spaces designed to support workers during they day, including zones purposely assigned for formal and informal meetings, collaboration, concentration, phone calls, relaxation, etc. In Australia, ABW spaces may or may not remove

desk ownership and that is highly dependent on the organizations' interpretation of ABW, needs and culture. Even when ownership is removed, some territoriality may take place through the popular concepts of neighbourhood and villages – this means that workers' do not own a workstation but they may work from the same zone within a floor. Demographics and basic fit-out information is summarized on Table 1 below.

Table 1. Basic information about surveyed buildings.

Building	Layout	Tenant Net Lettable Area (m <sup>2</sup> )	Number of monitored floors	HVAC
A	Combi	12,822	3	Yes
B	Combi	-	1	Yes
C	Combi	1,921	1	Yes
D	Combi	48,284	3	Yes
E	Combi	19,682	3	Yes
F	Combi	23,725	3	Yes
G	ABW	-	1	Yes
H	ABW	65,664	5	Yes
I	ABW	-	3	Yes
I	ABW	39,000	3	Yes

The BOSSA Nova mobile cart was used to conduct spot measurements of thermal comfort, acoustics, lighting and indoor air quality were taken in the morning and afternoon. The cart is able to take air temperature, globe temperature and air speed at three heights (0.2, 0.6 and 1.1m). The cart is also equipped with an indoor air quality rack. Portable light meter and sound pressure meter also available and by being attached to long cables, they can be taken from the cart for the purposes of readings. All sensors are connected to a datalogger and the readings can be monitored real time during the experiments.



Figure 1. The BOSSA Nova IEQ cart.

All measurements were taken from the occupied zone, near a workstation (0.50m radius from office worker) and during occupied hours (9am to 6pm). Horizontal lux readings were taken from the workstation. Building occupants were allowed to develop their normal

activities while instrumental measurements were carried out. Readings were averaged for 15 minutes for each point and a total of 5 points per floor were monitored in each workspace, including one for each façade, interior and perimeter zones. With exception of building C, all others had three floors investigated during this study.

Independent sample t-test was carried out to examine whether different workplace layouts significantly affected IEQ parameters. However, one of the problems with this null hypothesis testing is that even the most trivial effect will become statistically significant if enough people are surveyed (Field, 2013). To solve this problem, the effect size (ES) measures were adopted to test how important these statistically significant differences really are. In this analysis, a common measure of ES—Cohen's  $d$  (Cohen, 1988, 1992), was adopted when comparing two means. It is calculated by Equation (1) and (2).

$$d = \frac{\mu_1 - \mu_2}{\sigma} \quad (1)$$

$$\sigma = \sqrt{\frac{(N_1-1)\sigma_1^2 + (N_2-1)\sigma_2^2}{N_1+N_2-2}} \quad (2)$$

where  $\mu_1$  and  $\mu_2$  refer to the mean value for two groups,  $N_1$  and  $N_2$  refer to the sample size of two groups.

Cohen suggested that  $d=0.2$  be considered a small effect size, 0.5 represents a medium effect size and 0.8 a large effect size (Cohen, 1988, 1992). This means that if two groups' means do not differ by 0.2 standard deviations or more, the difference is trivial, even if it is statistically significant (Statistics for Psychology, accessed on 07-01-2017). The authors explain that a medium or large size effect is of more practical meaning in the real world than the small size one. All the statistical analysis was conducted in IBM SPSS, Version 22.

## Results

Results from independent t-tests are depicted on Table 2 and Figures 1 to 4 below summarise results for operative temperature, air speed, relative humidity and illuminance. The mean air temperature values recorded in ABW and combi offices were almost the same ( $22.7^\circ\text{C}$  and  $22.0^\circ\text{C}$ , respectively), however t-tests of all data indicate a small-size effect. All workspaces investigated here are fully air-conditioned and buildings are less than 10 years old so the type and air of base building HVAC is comparable. The range of air temperature values measured during field studies were consistent with those expected in air-conditioned buildings in Australia, where a narrow temperature set point is widely used.

As depicted on Table 1, analysis of the IEQ monitored data indicate that the mean radiant temperature was significantly lower in ABW settings than in open-plan offices, representing a medium-sized effect. Relative humidity was also significantly lower in ABW offices, representing a medium-sized effect. Higher illuminance was observed in ABW settings, representing a medium-sized effect.

Table 1. Independent samples t-test results for measured IEQ variables.

		Mean	Sig. (2-tailed)	Effect Size
Ta (°C)	ABW	22.7	0.001	0.28
	Combi	22.9		
MRT (°C)	ABW	22.7	0.001	0.56
	Combi	23.1		
Top (°C)	ABW	22.7	0.001	0.42
	Combi	23.0		
Va (m/s)	ABW	.07	0.001	0.30
	Combi	.08		
RH (%)	ABW	40.9	0.001	0.47
	Combi	44.8		
CO	ABW	1.04	NS	0.09
	Combi	1.08		
CO2	ABW	814.1	NS	0.29
	Combi	787.6		
TVOC	ABW	1.34	NS	0.33
	Combi	1.31		
Formaldehyde	ABW	.050	NS	0.24
	Combi	.046		
SPL (dBA)	ABW	50.9	NS	0.00
	Combi	50.9		
Illuminance (lux)	ABW	569.3	0.002	0.50
	Combi	437.6		

NS-Not significant.

In regards to indoor air quality (including carbon monoxide, carbon dioxide, TVOC, and formaldehyde), there was no significant difference observed between ABW offices and open-plan environments, confirmed by independent samples t-test conducted for this paper. This is not surprising considering that these buildings hold a green certification and as such, have more strict requirements around materials and products in use. Readings for carbon monoxide, carbon dioxide and formaldehyde were within recommended thresholds.

In addition, there were no significant differences for sound pressure levels and results are depicted on Table 1. Considering the open plan nature observed in both layouts, this result is not surprising. That said, mean SPL values recorded during occupied hours were higher than the recommended threshold in Australia (45dBA).

Floor plan analysis may provide some insight into differences observed on IEQ measurements in ABW and combi. ABW offices investigated here present a physical arrangement that is more open, with less vertical barriers (such as partitions and walls) and have considerably more spaces purposefully allocated for collaboration and overall incidental interaction including lounges, cafes and a mix of break out areas. Combined, these features may allow airflow to circulate more freely – please see Figure 3. All ABW environments

investigated here implemented biophilia principles, having significantly more indoor air plants throughout workspaces than combi offices. This may in turn be influencing relative humidity readings depicted on Figure 4.

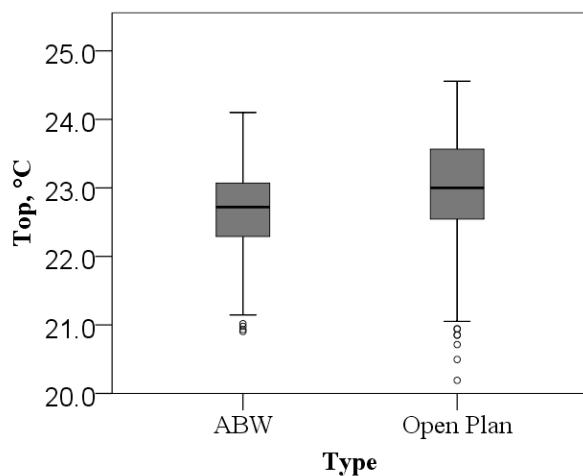


Figure 2. Operative temperature.

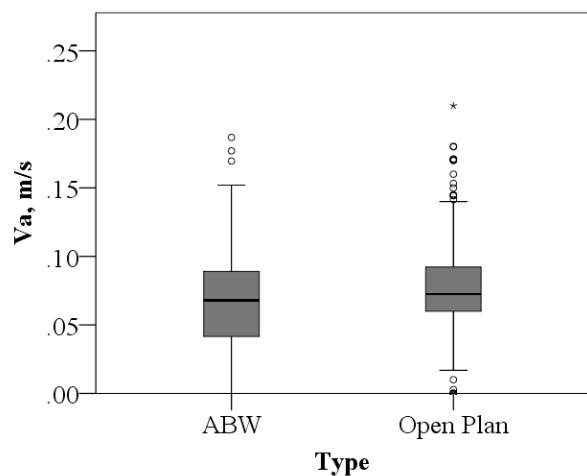


Figure 3. Air speed.

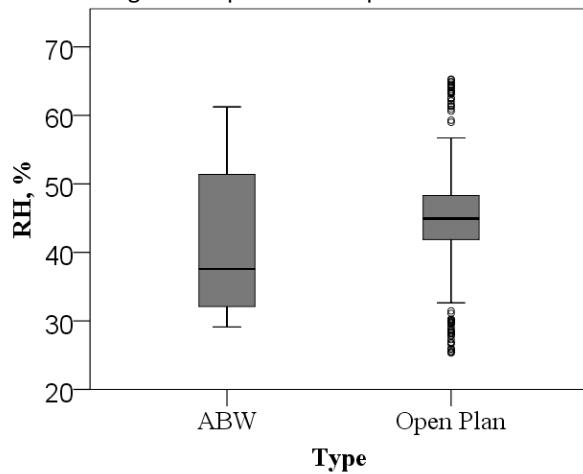


Figure 4. Relative humidity.

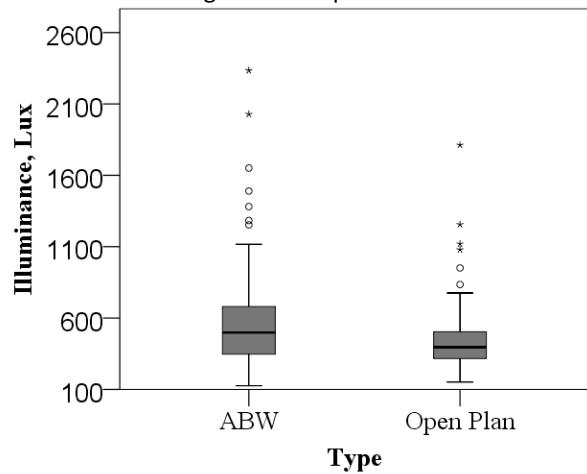


Figure 5. Illuminance.

In addition, these spaces also present more access to daylight due to the use of atriums as an architectural feature. In the ABW offices investigated here, a considerable amount of workstations in the ‘interior’ zone of the building are located near an atrium and these locations were sampled. In addition, there are workstations near the exterior façade of the building and these locations in ABW offices may be popular with occupants, especially if there is a view. Again, these sampling points were included during the IEQ monitoring presented here (please see Figure 5).

The activity-based mode of working may encourage building occupants to work from spaces that are more suited to their own individual preferences, including those relevant to IEQ, namely, thermal, lighting and acoustic conditions. In practical terms, if the potential to create microclimates is combined with mobility, workers may be able to select, from the space-menu available to them in ABW workspaces, zones there are less/more noisy, hot/colder, with more/less light, etc. This flexibility may help compensating for the lack of personal control systems and adaptive opportunities commonly observed in air-conditioned, open plan offices and in turn increase workers’ satisfaction.

## **Conclusions**

This paper compared monitored IEQ conditions of ten contemporary open-plan workspaces with ABW or combi layouts in green-certified buildings in Australia. Results indicate that combi offices were slightly warmer, had lower air speed values and were slightly less humid than ABW workspace. Results from Indoor Air Quality measurements of TVOC, formaldehyde, CO and CO<sub>2</sub> were similar in both settings while higher illuminance was observed in ABW offices. All workspaces investigated here are representative of contemporary offices and, not surprisingly, there were no significant differences for sound pressure levels. Although the difference of air temperature, operative temperature and air speed between different layouts reached high statistical significance, they only represent small-sized effects. The results presented here are limited to the case studies, however, they suggest the need to properly consider and adapt layouts and building features when designing Activity-Based Working environments.

## **Acknowledgment**

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## **References**

- Active Design Guidelines. (2010) NYC. <http://centerforactivedesign.org/guidelines/>
- Appel-Meulenbroek, R., Oldman, T. and Susante, P. van. (2016). How employees value the support of activity based and traditional work environment. In: Proceedings of the CIB World Building Congress, v. 4, p. 296–304.
- Brunia, S., De Been, I., Voordt, T. J. M. van der. (2016). Accommodating new ways of working: lessons from best practices and worst cases. Journal of Corporate Real Estate, v.18 (1), 30–47.
- Candido, C. M., Kim, J., de Dear, R., Thomas, L. (2016). BOSSA: A multidimensional Post-Occupancy Evaluation tool. Building Research and Information (Print). v.44(2), p. 214-228.
- Candido, C., Zhang, F., Kim, J., de Dear, R., Thomas, L., Joko, C., Strapasson, P. (2016). Impact of workspace layout on occupant satisfaction, perceived health and productivity. In: Proceedings of 9th Windsor Conference: Making Comfort Relevant. Cumberland Lodge, Windsor, UK, 7-10 April 2016.
- Candido, C. and Zhang, F. (2017). Workers' satisfaction in contemporary open-plan offices: a case-study comparison in Australian premium workspaces. In: 24th Conference of the European Real Estate Society, June 28 - July 1, 2017, Delft.
- De Been, I. and Beijer, M. (2014). The influence of office type on satisfaction and perceived productivity support, Journal of Facilities Management, v. 12 (2) p. 142-157.
- De Croon, E., Sluiter, J., Kuijer, P.P. and Frings-Dresen, M. (2005). The effect of office concepts on worker health and performance: a systematic review of the literature, Ergonomics, v. 48 (2), p. 119-134.
- De Paoli, D., Arge, K., Blakstad, S.H. (2013). Creating business value with open space ABW offices, Journal of Corporate Real Estate, v. 15 (3-4) p. 181-193.



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*Design to Thrive*

## Enhance: The Assembly Rooms Energy Living Lab

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**Abstract:** Enhance is a digital innovation project aimed at understanding and reducing energy demand in public sector buildings. The Assembly Rooms, an iconic events space in the centre of Edinburgh, is one of many public buildings in the UK with ongoing pressures to reduce energy use. Better awareness of energy and the ability to manage its use in the building has been achieved since the installation of an Energy Management System. However, large amounts the building's energy use are associated with 'unregulated' energy, often aligned to individuals and groups of building users. Involving building users in the management of energy use creates opportunities to link between 'hard' technical systems and the 'soft' social structures that exist in the public realm and design for the cultures and practices that lead to better ways of using energy. A Living Lab approach is being used to explore the energy demand in the Assembly Rooms relating to its day-to-day operations. Working with the venue team, the Enhance project is identifying opportunities for reducing energy demand via behaviour change. Designed interventions will connect people with digital artefacts and sensors to help create engaging and responsive interactions with energy use.

**Keywords:** Energy, Behaviour Change, Public Sector

### Introduction

The Assembly Rooms, originally opened in 1787, is a multi-purpose events space housed in a historic building in the centre of Edinburgh. Along with many public buildings in the UK there are ongoing pressures to reduce energy use. Enhance is a digital innovation project which is taking the form of a Living Lab in the Assembly Rooms aimed at raising awareness of and reducing energy demand. Building users are involved in understanding energy use relating to everyday activities in the building, developing ways of seeing energy use in an accessible digital form and designing approaches using the digital data to avoid wasteful energy practices.

The wider context of the project is threefold: as a public building it is required to contribute to reduce carbon emissions of 80% by 2050 (DECC 2014); as a historic building it has constraints that impact on energy use; and as a cultural venue it has a varied client body with distinct energy requirements. Each of these contexts influences energy use in the Assembly Rooms, which is owned and operated by the city council. As part of a public sector estate, it is governed by the policies and regulatory framework of the wider organisation, while simultaneously operating as business in its own right. The historic status of the building limits the fabric interventions that can be done to improve energy efficiency. For example, the historically important chandeliers, each comprising hundreds of bulbs, currently have

standard fittings to meet the requirements for aesthetics and warmth of light. The Assembly Rooms was designed for public assemblies, dances and concerts and this use continues to today. The building has two main assembly spaces and associated circulation, and ancillary spaces, providing facilities for varied events throughout the year. There is complexity in the relationship of energy use, the diverse range of events held, and the priorities of the client.

The inception of the Living Lab was through a series of interactions with the city council to explore the idea of energy use for large organisations. It became evident that both explicit and tacit knowledge of energy use was used across the organisation, much of this with individuals and groups of people within individual buildings. This resulted in the selection of the Assembly Rooms as the location for researching energy use within the wider context of the city council. The Living Lab is unfolding through a year in the life of the building, and has three evolutionary phases – contextualisation and insight research; co-design and implementation; and evaluation. Throughout each of these phases individuals and groups of building users inform and shape the course of the research.

### **Energy Use in ‘Smart’ Public Buildings**

The increasingly popular concept of ‘Smart Buildings’ is synonymous with an energy management system designed to optimise energy use. This fascination with automated energy systems has resulted in the installation of energy management systems to control devices and systems as and when they are needed. Evidence from EU pilot projects shows the positive impact of this on energy reduction (Janez Moran et al. 2016). Many of the systems installed through these projects required expert knowledge to operate. This then leads to buildings where the energy system is separated from the people using the building, which in turn leads to a diminished sense of responsibility for energy use. As a result, systems are often configured to provide thermal or lighting conditions that are inappropriate for the activities taking place. This centralisation of energy control to complex and sophisticated management systems has been shown to undermine their effectiveness (Goulden & Spence 2015). Better integration between the energy systems and the activities taking place within a building can be used to negotiate the energy domain that is vital for a comfortable, pleasant, enjoyable environment.

### **Energy Use and Building Users**

Janda (2011) reinforces the connection between building users and energy use. The relationship between people and energy in public buildings presents specific challenges. Public buildings have a wide range of user groups, from long term regular workers occupying the building on a daily basis; to business clients; to regular visitors; to fleeting users visiting the building only once. With this range comes a quickly diminishing familiarity with, and responsibility for energy use. This suggests that building users cannot be defined with a set of homogenous characteristics - a factor that is not accounted for by existing building management systems. Janez Moran et al. (2016) reinforced the need for creating different approaches for energy management depending on the typology of the building user, to both raise awareness and engage with behaviour change.

In events buildings, energy use varies considerably with the type of event. While always affected by seasonal and daily outside conditions it is also influenced by client specific requirements: audio-visual needs; the energy efficiency and the type of equipment used; the thermal and lighting conditions required by the client; and the characteristics, activity-

level, and dress code of the clients. This demonstrates the complexity in the parameters for creating the right environmental conditions for a particular event.

### ***Involvement of Building Users***

People within a building have direct and indirect influence and control over energy used. The Living Lab taking place in the Assembly Rooms is providing opportunities for the different group of people who work in and use the building to consider modes of use that lead to energy demand. Gaetani et al. (2016) refers to using a fit-for-purpose model for building energy that reflects the typology of the people and building. Interactions between people and the energy system are considered important for validating the setting, but also to harness the psychological effect of retaining a perception of an element of control over ones' environment.

### **Methodology**

Living lab research engages people within their everyday settings to identify opportunities and solutions through processes of exploration and co-design. The approach encompasses five key principles:

1. **Continuity:** conducting the research over a continuous and lengthy period enables close and trustworthy partnerships to be established.
2. **Openness:** incorporating different viewpoints and contributions from various stakeholders leads to an inclusive and open-minded approach.
3. **Realism:** the research takes place in real-world settings, facilitating close collaboration, in-depth understanding, and ecological validity.
4. **Empowerment:** stakeholders are given active roles in shaping the course of the research and defining its outcomes.
5. **Spontaneity:** the approach affords the flexibility to respond and adjust to unforeseen changes in circumstances.

These principles are essential in building trust with the participants. Based of work by Pierson & Lievens (2005), Kareborn & Stahlbrost (2009) and Baedeker et al. (2014), three phases of the Living Lab are used to provide a framework for an extended period of engaging with the building users. Each phase is designed to contribute to the overall aim of the evolutionary nature of the research. The first phase lays the foundations for the living lab, establishing its context and conducting insight research to build relationships and investigate the existing status-quo with respect to the topic of interest. The second phase involves the co-design and deployment of an intervention (technology or service), based upon the challenges and opportunities identified in phase one. During the third phase, feedback and data are collected and analysed to assess the adoption and impacts of the intervention. The latter two phases of this framework can be iterated to provide an ongoing process of evaluation and re-design. The Enhance Living Lab is currently entering its second phase. The following paragraphs provide details on some of the exiting methods that have been employed, as well as plans for the co-design and deployment phase.

### ***Phase 1: Contextualisation and Insight Research***

The selection of the Assembly Rooms as a site for the Enhance Living Lab was the result of early meetings with senior managers in the city council and a consideration of the project from the context of a large organisation. Over a period of three months the concept of

engaging building users in a Living Lab was used to explore the building typologies that present interesting challenges for the council in its aim to reduce energy demand across its stock. Site visits and staff interviews were conducted to evaluate the suitability of each potential building. The Assembly Rooms was chosen due to the high levels of control and influence over energy use available to building users, as well as the diverse and complex challenges associated with its function as an event venue for external clients.

Introducing the project to the people working within the Assembly Rooms was facilitated through a series of workshops conducted with all the permanent staff in the building and some of the regular staff from outsourced contractors. These workshops were also designed to investigate energy narratives around the building in the context of everyday activities. In particular, the intention was to explore the behavioural pathways that link people to the building fabric and systems that ultimately determine energy consumption. Workshop participants were first asked to individually identify material aspects of the Assembly Rooms that they felt presented good opportunities for energy saving. These were then shared amongst the group, and the two most prominent opportunities were taken forward for further consideration. In groups of two, participants were then asked to identify people (groups or individuals) who have influence or control over these factors, and to arrange them with the energy saving opportunity at the centre (see Figure 1). Participants then annotated pathways of influence or control between people and the energy use, and between different types of people. The workshop participants identified potential interventions that could influence the different energy pathways.



Figure 1. a) Staff at the Assembly Rooms attend an initial workshop. b) A map of pathways of influence and control between people and heating/insulation.

These workshops succeeded in revealing inter-related threads that create a holistic view of the complexities of building users' relationships to energy use. To supplement the predominantly qualitative nature of the workshops, quantitative data relating to energy use in the Assembly Rooms were captured. Existing data on electricity and gas metering for the whole building was provided by the council. In addition custom data was recorded from the existing control systems to accurately monitor lighting and building management system (BMS) parameters for the purpose of the project. This data collection serves several functions: a) it allows baseline energy usage to be captured prior to the deployment of an intervention; b) it provides a potential source of raw data to feed into an energy feedback intervention; c) when visualised, it can be used to stimulate discussion and realisations about energy use. Regarding the latter point, visualisations of lighting and electricity use were created and

presented in the workshops and early meetings with staff (see Figure 2 for examples). These prompted staff members to provide a qualitative and descriptive layer to the visualisations, based upon their knowledge of the building's use. This led to the identification of specific issues and opportunities surrounding energy use in the Assembly Rooms.

In summary, the first phase of the Assembly Rooms living lab explored the context in which the research is being conducted, developing a rich qualitative understanding of energy use from the building users' perspectives, whilst also ensuring that valuable quantitative data are captured from the building's energy systems. Working closely with diverse teams of staff has provided them with a sense of ownership in the process, and enabled the development of trust and understanding between the stakeholders and researchers. Furthermore, by providing a platform to all who had an interest in the project, the potential for building users to engage in energy use was incorporated. Emerging findings from this work are discussed later in this paper. These findings will inform and shape the second and third phases of the project, which are outlined briefly below.

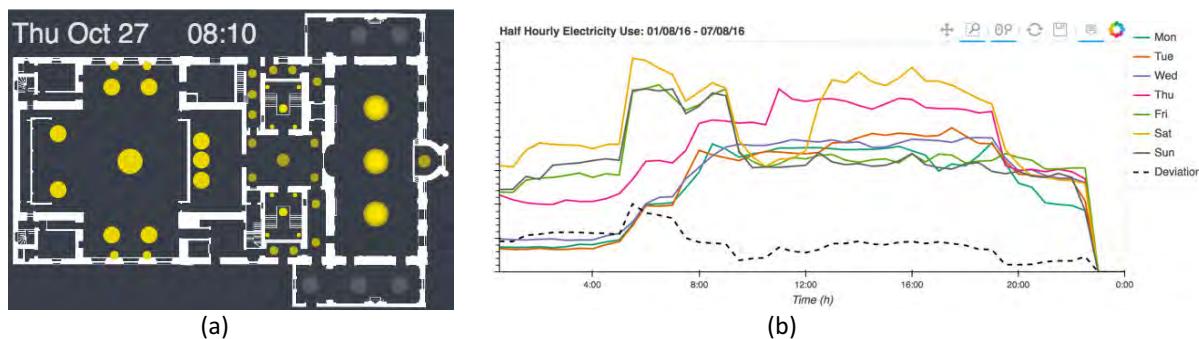


Figure 2. Data visualisations of a) lighting use according to time and location; and b) hourly electricity use.

### **Phases 2 and 3: Co-design and Evaluation**

The goal of the second phase of the project, which is currently in its early stages, is to design and develop a digital innovation that will facilitate behaviour-based energy savings at the Assembly Rooms. Building upon work carried out during phase 1, and especially the interactions and relationships developed with staff, an 'innovation team' has been established. The aim is to design, develop and prototype an initial innovation incorporating digital data to respond to the energy pathways plotted in phase 1. This team will participate in co-design workshops with designers and researchers on the Enhance project to develop and prototype an initial innovation. Following the deployment of this innovation, the third phase will involve evaluating its usage and impact within the building. Again, this will involve a mixed approach employing qualitative methods, such as interviews and focus groups, alongside quantitative analyses of data relating to energy use and interactions with the innovation; the results from which will contribute to further development and iterations of the innovation. The reflective and responsive approach is strengthened by involving building users fully in the design and utilisation phase.

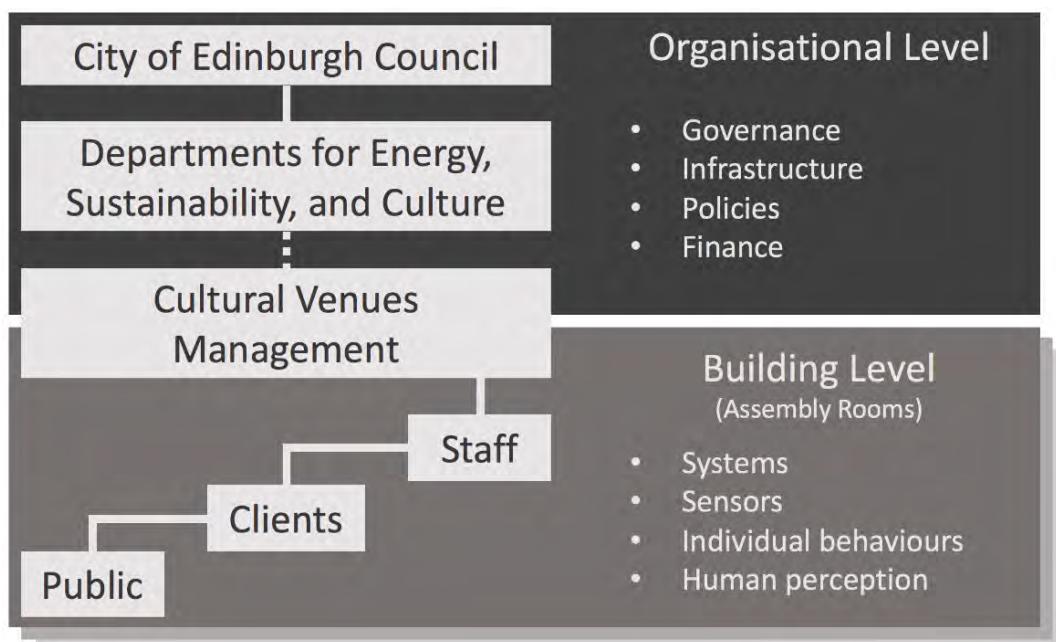


Figure 3. A representation of the organisational structure and factors that frame the Assembly Rooms within the wider City of Edinburgh Council.

## Emerging Findings

### *The Building within the Public Sector Estate*

Figure 3 shows the position of the building organisation relative to the broad organisational structure of the council. The Assembly Rooms, while operating as an independent venue, has formal and informal influence on energy use and sustainability from the wider council agenda, policies and systems. The opening phase of the Living Lab, working with the senior managers in the council, provided the dual purpose of both identifying the building to work in and understanding the wider organisation, from management to building users. Although the council has a commitment to reduce carbon emissions in its building stock by 80% of the 1990 rate by 2050, this specific responsibility is not associated with any senior role within the council, or within the individual building level organisation.

From an organisational level, targets to reduce energy use translated into 'hard' infrastructure changes. The Energy department worked closely with the building management to install appropriate energy control systems (lighting and heating/ventilation) where technologies and venue requirements permitted. Therefore, at senior management level it was perceived that they had a large influence on energy use in the buildings. Across many council buildings EMS installation facilitates control of energy systems, however these systems were not found to be used for energy monitoring and feedback purposes to any great extent or granularity. Thus, full advantage was not taken of these tools for data monitoring and identification of possible opportunities to further reduce energy demand in buildings. The lack of utilisation and cohesive storing of energy data also posed a difficulty for senior management in the ability to clearly assess and evaluate gains and improvements in energy use across the estate. Installation of the 'hard' EMS systems (lighting and heating/ventilation) in the Assembly Rooms were not designed to have a reciprocal relationship with the 'soft' social structures and the complex relationships between people and energy. This has been shown to have an impact on the gap between expected energy use and actual building performance occur (Gaetani 2016).

It was apparent that from building users' perspectives they felt the council organisation had little influence and impact on daily energy use in the Assembly Rooms. It was the initiatives and personal drive of building managers and staff which led them to target energy reduction through behavioural actions and to strive for external acknowledgements on their performance (eg Green Tourism Awards). The staff of the building take pride and are motivated in achieving these awards, using them in the promotion of the venue. This has been shown to be an important influence on employees' environmental perspectives (Onkila 2015).

### ***The Building as an Energy System***

The Assembly Rooms has a relatively modern EMS, which facilitates thermal control over individual spaces and is configured on a per-event basis by the events and facilities managers. The system can also provide graphs of energy usage data over previous weeks, however, this functionality is rarely used. The lighting in the building is controlled via a network-based iLight system, with control panels situated in each room to enable building users to make localised lighting adjustments. These panels are configured by the production manager, who has fine grained control over parameters such the maximum brightness and dimming behaviour of individual lights. In this case, specific adjustments have been made to the lighting system to reduce energy use and prolong the life of light bulbs.

Looking beyond the EMS and lighting systems, the workshops and data visualisation described in the previous section paint a more holistic view of the Assembly Rooms as an energy system incorporating not just materials and systems, but people - their behaviours, responsibilities, interactions, and relationships. Analyses of the workshops have revealed findings and insights at both a generalised building level, and at lower, person/group-specific levels. When considering material aspects of the building, workshop participants most frequently identified lighting, heating, and equipment use as opportunities for behaviour-based energy savings. Of the people identified as having control or influence over these forms of energy use, clients emerged as the most prominent, whilst the council were rarely discussed (fig 4). This is an important finding, since it suggests that staff do not recognise the council as having significant control or influence over energy use. As such, they may be less likely to respond to, or feel any ownership of, energy saving projects which are set by corporate services.

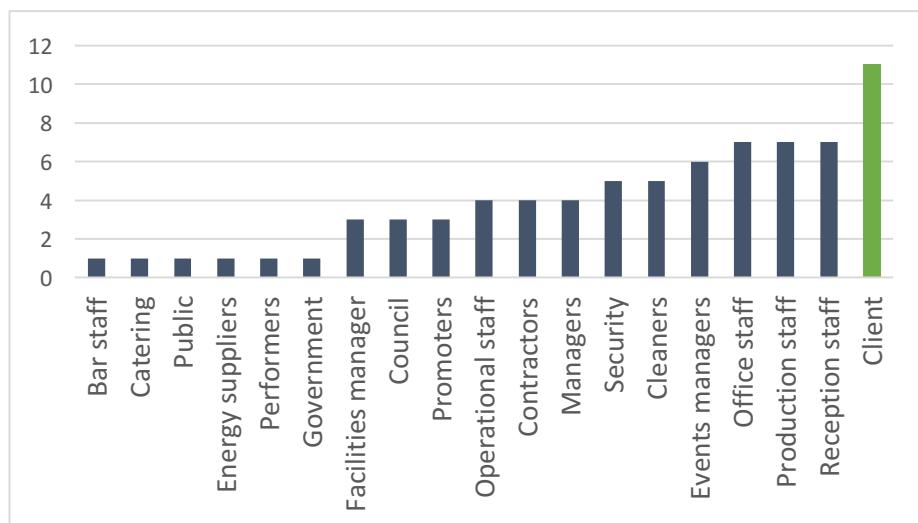


Figure 4. People perceived to have control or influence over energy use

The three most commonly identified forms of behavioural influence or control over energy use were direct lighting adjustments, requested changes, and event requirements. Again, this indicates a focus on the client as having a dominant influence on factors relating to energy use. With respect to potential interventions, training, information, and feedback were the three most frequently proposed ideas. This finding supports existing studies that have cited lack of feedback on personal actions as an important barrier to energy saving behaviours in large organisations (Carrico & Riemer 2011)

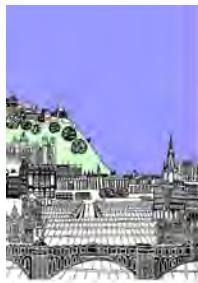
At a lower level of analysis, the workshops revealed particular interactions between individuals or groups of people, which have a subsequent impact upon energy use. For example, in the lead up to an event, discussions between the sales team and client will determine how the event space and facilities are used. During an event, attendees will often make requests for changes to heating, either directly to the events staff, or via the client. As the research progresses into the second, co-design phase, these insights will be used to channel attention towards specific interactions that could be the target of a digital intervention.

## Conclusions

Energy use is correlated closely to the activities taking place in the building. Large events can be mapped against big increases in energy use. While this can be expected, the challenge for the Assembly Room teams is to manage the need for energy use for the core business activity of the venue, while working within a public organisation with a commitment to reducing energy. Finding ways of providing a socio-technical system that is responsive to energy demand in harmony comfort and enjoyment for the activities taking place is vital for a successful integration of energy use into the everyday life of the building.

## References

- Baedeker, C. et al., 2014. Transition through sustainable Product and Service Innovations in Sustainable Living Labs: application of user-centred research methodology within four Living Labs in Northern Europe. In 5th International Sustainable Transitions (IST) Conference. Utrecht, The Netherlands. Available at: [http://suslabnwe.eu/fileadmin/suslab/Images/IST-5thconference\\_SusLabNWE.pdf](http://suslabnwe.eu/fileadmin/suslab/Images/IST-5thconference_SusLabNWE.pdf).
- Carrico, A.R. & Riemer, M., 2011. Motivating energy conservation in the workplace: An evaluation of the use of group-level feedback and peer education. *Journal of Environmental Psychology*, 31(1), pp.1–13. Available at: <http://www.sciencedirect.com/science/article/pii/S0272494410001015> [Accessed March 14, 2016].
- Department of Energy and Climate Change, 2014. Developing DECC's Evidence Base, Available at: [www.gov.uk/decc](http://www.gov.uk/decc).
- Gaetani, I., Hoes, P.-J. & Hensen, J.L.M., 2016. Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy. *Energy and Buildings*, 121, pp.188–204. Available at: <http://www.sciencedirect.com/science/article/pii/S0378778816301918> [Accessed April 6, 2017].
- Goulden, M. & Spence, A., 2015. Caught in the middle: The role of the Facilities Manager in organisational energy use. *Energy Policy*, 85, pp.280–287. Available at: <http://dx.doi.org/10.1016/j.enpol.2015.06.014>.
- Janda, K., 2011. Buildings don't use energy - People do! *Architectural Science Review*, 54, pp.15–21.
- Janez Moran, A. et al., 2016. Information and Communications Technologies (ICTs) for energy efficiency in buildings: Review and analysis of results from EU pilot projects. *Energy and Buildings*, 127, pp.128–137.
- Kareborn, B.B. & Stahlbrost, A., 2009. Living Lab: an open and citizen-centric approach for innovation. *International Journal of Innovation and Regional Development*, 1(4), p.356.
- Onkila, T., 2015. Pride or Embarrassment? Employees' Emotions and Corporate Social Responsibility. *Corporate Social Responsibility and Environmental Management*, 22(4), pp.222–236. Available at: <http://doi.wiley.com/10.1002/csr.1340> [Accessed April 7, 2017].
- Pierson, J. & Lievens, B., 2005. Configuring Living Labs For A 'Thick' Understanding Of Innovation. *Ethnographic Praxis in Industry Conference Proceedings*, 2005(1), pp.114–127. Available at: <http://doi.wiley.com/10.1111/j.1559-8918.2005.tb00012.x>.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Seven key lessons from Active House demonstration buildings

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**Abstract:** A study on eight demonstration project that include six single-family homes, a school and a kindergarten, shows that the indoor climate can be optimized in energy efficient buildings that meet the Nearly Zero Energy demand. The buildings evaluated is a part of the VELUX model home 2020 program and it follows the Active House principles and are evaluated on the parameters Comfort, Energy and Environment. The eight buildings are optimized to meet a nZEB level and are thereby highly energy efficient. They use where possible passive solutions like solar energy, daylight, natural ventilation, shading and ventilative cooling. Solutions that optimize the performance of the building without use of energy. The paper discusses the challenges, the experience and the need for update of legislation and compliance tools in seven key points.

**Keywords:** Model Home 2020, Active House, Comfort, Daylight, Natural ventilation

### Introduction

The existing legislation on energy efficiency of buildings like the European Directive on Energy Performance of Buildings sets requirement to develop Nearly Zero Energy buildings.

Unfortunately such legislation do not take into consideration the indoor comfort levels of buildings and do not set requirement to topics like minimum daylight conditions, indoor air quality, topics that are important for users of the building. Having in mind that people use energy in buildings in order to create a good indoor comfort level, such energy requirement should always be followed by indoor climate requirement.

An example is that the daylight conditions in buildings is reduced due to smaller windows with thicker glass, or thermal comfort in summer period is to hot due to lack of ventilation. In order to balance the above to the human needs, energy for artificial light or cooling is requires. The question is if there are solutions that can optimize the energy efficiency of the building and create a good indoor comfort level with minimum use of energy.

The answer is yes.

### From data to knowledge

Eight demonstration buildings (fig 1) has been evaluated and the performance monitored in terms of daylight, thermal comfort, indoor air quality and ventilation. The analyses focuses on an array of different subjects such as operation routines, temperature fluctuation and CO<sub>2</sub>-levels and uses detailed technical evaluation as well as personal feedback from the residents to create valuable knowledge on how to optimise the overall performance of the buildings.



The eight evaluated houses:

First row from left: Maison air et Lumière (F), LichtAktiv Haus (D), Sunlighthouse (A), CarbonLight Home (UK)  
 Second row from left: Home for Life (DK), Active House Russia (Rus), Endrup School (DK), Solhuset Kindergarten (DK)

Fig 1: The eight evaluated projects

The survey comprises six single-family homes, an elementary school and a kindergarten. Five of the six detached family homes are part of the VELUX Model Home 2020, a full-scale European development project, aimed to showcase sustainable buildings in a 2020 concept equal to Nearly Zero Energy buildings and based on the Active House principles. The remaining 3 buildings are designed with focus on the Active House principles, balancing comfort, energy and environment. Thereby all eight projects are designed as Active House.

### **Seven key learnings and recommendations**

The survey was based on a combination between monitoring the energy saving and the indoor climate conditions, in combination with people's behaviour and their interest in acting on signals to change their behavior.

Several key learnings were obtained through the study and below seven key points is described in a structure with challenges, experience and observations, as well as recommendations for new legislation and requirements to design of nZEB projects.

#### ***Key point 1: Many and large windows doesn't necessarily lead to overheating***

##### *Challenge*

A main requirement to the eight demonstration projects were that the individual rooms in the buildings should reach a daylight factor of 5% or more. Plenty of daylight usually requires big window solutions with a large area of window pane. Large windows, however, can also lead to excessive solar heating, which is a problem, especially in low energy buildings during the summertime. This creates a risk for overheating which should be avoided.

##### *Experience*

The study shows that the test families and the users of the buildings find large window areas very attractive with a good interaction between inside and outside, as well as they prefer to utilize the daylight conditions and ignore use of electrical lighting as long as possible.

The design of the building allows for activation of shading in order to reduce the risk for overheating, as well as the building allows for ventilative cooling. As those shadings and ventilation solutions were activated when needed, the risk for overheating was reduced, like in Maison Air et Lumière (fig 2).

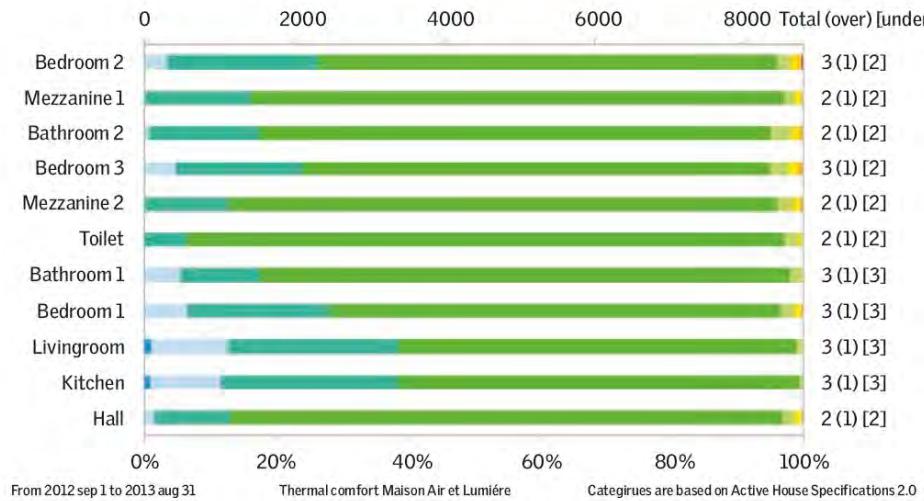


Figure 2 Thermal comfort in building with large window areas

Five out of the six monitored buildings achieved the highest possible score for thermal comfort, indicating that the risk for overheating had been reduced to a minimal problem.

#### *Recommendation*

Nearly Zero Energy Buildings with daylight factors of 5% or more can be designed without risk for overheating, if a strategy for reducing the risk of overheating is included. This strategy shall include ventilative cooling and external shading.

As there is a risk of overheating in well insulated buildings like nZEB, the legislative requirement to nZEB should be followed by a legislative requirement to prove indoor thermal comfort levels based on the adaptable methods in the European standard EN 15251.

#### ***Key point 2: Plenty of daylight eliminates your need for artificial lighting during the day***

#### *Challenge*

When people wake up in the morning or return from work most people turn on the electrical lighting. This is due to the fact that people sense that the building and home is too dark for comfort and too dark for functional activities like cooking, reading etc.

#### *Experience*

The majority of the evaluated buildings address the issue with a comprehensive window solution that seeks to maximise daylight availability throughout the day. Due to this “daylight autonomy”, where daylight is used to reach a certain lux level through the use of just daylight, it was proven that most families and users of the building altered their lighting routine and stopped using artificial lighting from sunrise to sunset— even during the winter months. By the optimal design, no electric light was used between sunrise and sunset.

The kindergarten was as an example designed with minimum two windows with different orientation in each room and often three different orientations (Fig 3). This creates an indoor lux level where no electrical light was needed during daytime.

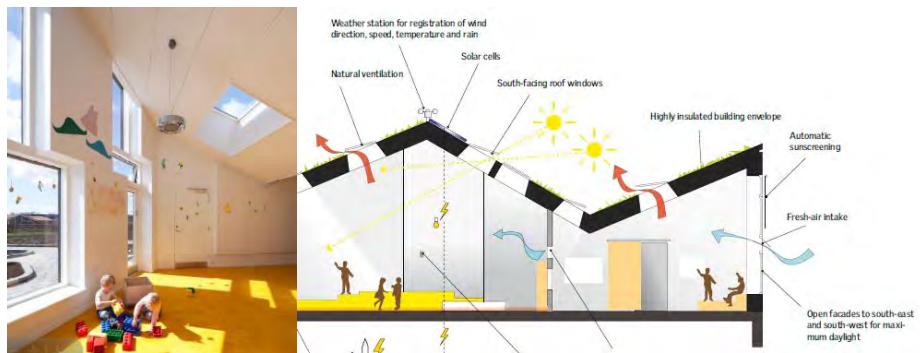


Figure 3: Windows to two different orientations create balanced daylight and support natural ventilation

#### *Recommendation*

Buildings with optimized daylight conditions can reduce the use of electricity for lighting, however as electricity for lighting is not included in energy calculations for dwellings, the savings by optimized daylight design is not visible for designers.

The legislative requirement to dwellings on nZEB levels should include electricity for lighting in the energy calculation and where relevant be based on a minimum indoor lux level during the use period of the building. The level can be from 300-550 Lux depending on the type of room.

#### ***Key point 3: Solar screening protects home from overheating***

#### *Challenge*

There is a risk that the utilisation of passive solar energy through windows, create high indoor temperatures during the summer period. This can be avoided by use of permanent solar shading, however permanent shading can also reduce the optimal utilization of passive solar energy and thereby the optimal situation is to use dynamic shading solutions.

#### *Experience*

The south and west orientated windows in the demonstration buildings were fitted with awning blinds to optimize the use of solar energy, to control the incoming solar energy and to maintain good thermal comfort.

The position of the awning blinds was registered throughout the day, monitoring the correlation between acceptable temperatures and the position of the awning blind. The results (fig 4) shows that overheating can be avoided even in buildings in hot summer conditions and with daylight factors of 5%. The study also shows that only a few hours during the year has a risk of overheating, and in the project shown in figure 2 only one day in May, July and August had overheating with shading activated.

#### *Recommendation*

Future lowenergy buildings and nZEB are already today calculated for summer and winter conditions, however the summer conditions are often calculated with solar protection factors that are pre-defined and therefor they do not give a real picture of the situation of the building.

In order to create accurate calculations, the legislation and compliance tools need to be updated and take into consideration dynamic solutions. An hourly based calculation methodology is needed to reach correct results and can be based on EN 15251

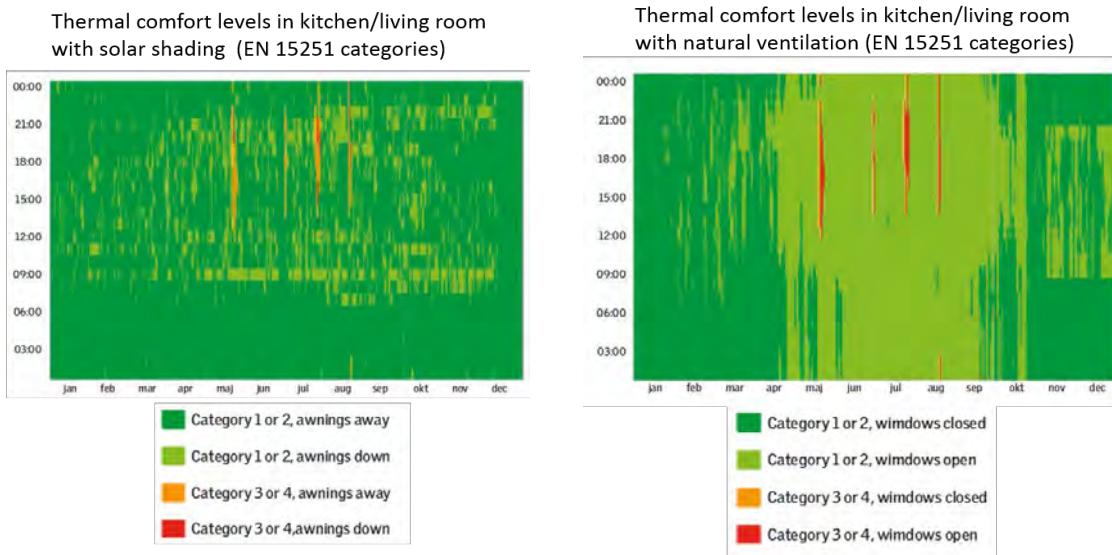


Figure 4 and 5: Thermal comfort with external dynamic shading or natural ventilation in kitchen/living room

#### **Key point 4: Natural ventilation lowers the temperature**

##### *Challenge*

Well insulated buildings like nZEB buildings are designed to keep the heat inside and to reduce the heat loss through the building envelope. This is an advantages during the heating period, however it can become a disadvantages during warm periods, especially in buildings that are designed to optimize the solar energy and to use thermal mass to store the heat, especially in rooms orientated towards west.

##### *Experience*

Ventilative cooling has been used in all eight demonstration projects to control solar heating, to reduce the indoor temperature in hot periods and to reduce night temperatures.

Ventilative cooling uses fresh outside air to reduce the room temperature, without use of electricity. By monitoring when the windows has been open for ventilation it has been possible to compare operation of windows with the given temperature level in the building. The results show a clear correlation between comfortable temperatures and the use of open windows (fig 5). Overheating was prevented 95% of the time and in the project shown in figure 3 only one day in May, June, July and August had overheating with ventilative cooling activated.

Parallel to this is was proven that all bedrooms generally have temperatures good for sleeping. Hence keeping the windows open during the night makes it possible to reduce the temperature by up to 6° C, reaching a comfortable level of about 20° C. Another important result is that ventilative cooling also reduced the CO<sub>2</sub> levels and created a healthy sleeping environment.

##### *Recommendation*

As mentioned within key point 4 above, it must be secured that the summer comfort levels in nZEB buildings can be kept on a comfortable temperature level and based on the adaptable methods in the EN 15251 and best by hourly calculations.

The legislative requirement should also set priorities for use of natural ventilation and ventilative cooling in order to reduce the need for energy for cooling and create possibilities for night cooling of not only dwellings, but also offices, schools and nurseries.

## **Key point 5: Moderate bedroom temperatures ensure a good night's sleep**

### **Challenge**

When people go to sleep, the body temperature drops naturally in order to save energy. Therefor many people want to have a low temperature in bedrooms and a warm bedroom will feel uncomfortable and lead to bad sleeping quality. This can be a risk in low energy buildings that are designed to optimize the solar energy and to use thermal mass to store the heat, especially in rooms orientated towards west.

### **Experience**

By use of optimal building design, which include orientation of the rooms depending on their needs, use of shadings and natural ventilation, the risk for hot sleeping rooms can be reduced.

In all five demonstration projects in the Model Home 2020 program there was observed a peak in temperature in the afternoon. After sunset, however, the temperature falls to a modest level, creating a pleasant sleeping environment – also during the important hours between 10pm and midnight. This was due to the utilization of ventilative cooling.

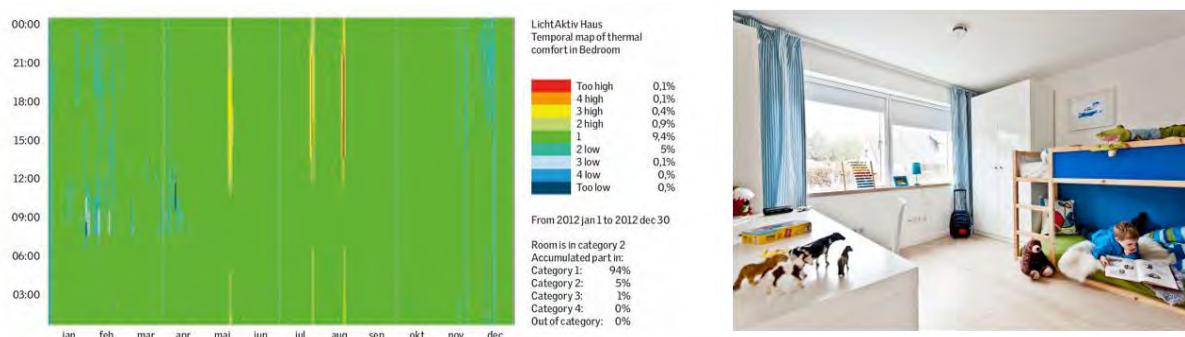


Figure 6: Thermal comfort in bedroom with natural ventilation

### **Recommendations**

Good sleeping conditions has an influence on people's health, wellbeing and productivity. Research shows that the indoor temperature should be around 16-19 °C for good sleeping quality.

Therefor legislative requirement future buildings and especially low energy buildings like nZEB should include requirement to indoor temperature levels in sleeping rooms at a level on ie. 19 °C.

## **Key point 6: Natural ventilation provides good air quality during large parts of the year**

### **Challenge**

In order to reduce air leakages and heat loss in energy efficient buildings, the building envelope has to be airtight. This reduce the uncontrolled air exchange of a room but it also sets requirement to a better controlled indoor climate with continuous ventilation to replace humid and CO<sub>2</sub> saturated air with clean, fresh outside air, where possible with use of as less energy as possible.

### **Experience**

The experience from the eight demonstration projects shows that the CO<sub>2</sub> levels in the demonstration buildings remained low during spring, summer and autumn due to use of natural ventilation.

It was also shown that the stack effect of ventilation in rooms with windows in the façade and roof created an effective ventilation, even with a small difference in temperature. Thereby it is shown that it is possible to create good indoor air quality without use of energy, during a large part of the year.

#### *Recommendation*

In order to reduce use of energy in nZEB, such buildings should utilize passive solutions as widely as possible. It has become a standard solution to use passive solar energy for heating and it is today a part of legislation and compliance tools to legislation.

It is however not the same with use of natural ventilation, where the legislative requirement are set to meet solutions that often only can be reached with mechanical ventilation, like a threshold barrier of a certain CO<sub>2</sub> level. Compliance tools as well as legislative requirements has to be updated to set prioritization for ventilation of buildings without use of energy. Such update includes threshold barriers that can be meet by use of natural ventilation, and legislation could be based on the classes in EN 15251.

#### **Key point 7: Kindergartens and schools benefit from scheduled, natural ventilation**

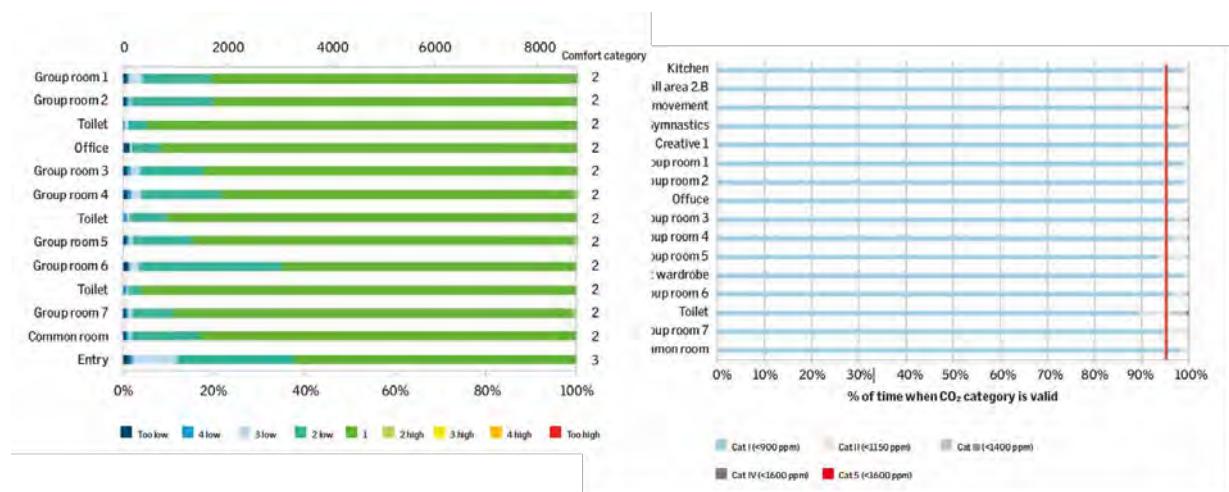
##### *Challenge*

Several studies shows that the learning abilities by school children and students are affected by the indoor climate conditions. Studies shows that it has an effect on the PISA results as well as it has socioeconomically consequences for the society.

##### *Experience*

The research and the monitored data from Solhuset Kindergarten clearly document the benefits of combining large fenestration with automated remote control in demanding learning environments.

As a new built kindergarten, Solhuset offers 3.5 times more daylight than what is required by current building regulations. While much of this daylight is turned into solar heating, the automated window openings and external solar screening helps to control the effect during the summertime and to create a pleasant indoor comfort level (fig 7).



Indoor comfort in Solhuset:

Left: Thermal comfort level shows that no rooms are overheated, even though the window area allows for 3.5 times better daylight.  
Right: A CO<sub>2</sub> level of < 900 PPM is reached in almost 95% of the time in all rooms

Figure 7 and 8: Thermal comfort level and indoor air quality during one year in Solhuset

Likewise CO<sub>2</sub> levels in the activity rooms are kept below 900 ppm in almost 95% of the

time in all rooms, creating pleasant environment for learning, play and relaxation (fig 8).

#### *Recommendation*

The indoor climate in schools and kindergartens should meet a level that create good learning abilities for children. Therefor fresh air, daylight and thermal comfort (as well as noise level) must be controlled.

The solutions brought forward can include mechanical ventilation, but as it is proven that natural ventilation can meet same level, the legislative requirement must be described without preferences for specific technical solutions. Such requirement can include the levels in EN 15251, and should also allow for solutions like rapid ventilation between lessons.

#### **References**

- J. Christoffersen, A. K. Hammelev Hansen, K. Andersen, P. Foldbjerg, T. Færing Asmussen (2016) VELUX A/S *Indoor climate in a renovated Danish school: Measurements of electric light, indoor temperature and air quality* Paper at CLIMA2016, Aalborg 2016.
- Bruno Peuportier ARMINES, CES , Karsten Duer, Christoffer Plesner and Nicolas Dupin VELUX A/S, (2013) *Evaluation of ventilative cooling in single family home*. Proceedings of AIVC 2013
- Pawel WARGOCKI (International Centre for Indoor Environment and Energy (ICIEE), DTU Civil Engineering, Technical University of Denmark (DTU)), Peter VELUX A/S (2014) *Socio- economic consequences of Improved Indoor Air Quality in Danish primary Schools*, Paper at Indoor Air, Hong Kong 2014
- Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). *Dynamic Daylight Performance Metrics for Sustainable Building Design*. Leukos, (3/1), 7-31
- CIBSE, (2014). *Daylighting - a Guide for Designers*. Lighting Guide 10/14 CIBSE.
- Active House (2013) *Active House specification - edition 2*. Active House Alliance, [www.activehouse.info](http://www.activehouse.info)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Form Follows Performance

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**Abstract:** There is a growing need in design and construction to be able to achieve low carbon architecture efficiently – more quickly and with less effort; but a growing sense that we are not doing as well as we could. A step-by-step approach to sustainability has been developed with design guidance on projects ranging from the smaller and simpler projects through to the larger and more complex, to help integrate green thinking more fully into the project programme. The objectives of this approach are to improve the design process within the construction industry into a smoother and more collaborative effort between the different disciplines involved; a process which has become more challenging with increasing geometric complexity and time pressures; requiring a more dynamic design process. These objectives are promoted through the integration of innovative technologies such as, parametric design. This research looks at merging sustainability in the overall design process with a series of Interactive Parametric Sustainable Design tools, which are designed to address specific questions. These questions are based on our experience and case studies, questions that arise in all types of project at different stages throughout the design process; leading us to ask “what if form were to follow performance”?

**Keywords:** high performance building, parametric simulation, sustainability guidelines, workflow, parametric tools.

### Introduction

Buildings are often certified as achieving high credentials, even though the people working on the design of those buildings are aware of the real challenges and the extent to which the design process has missed the opportunity to fully integrate sustainability principles. The lack of established guidance and practical design tools that incorporate performance criteria into the development of early stage analysis creates difficulties in efficiently exploring design options (Prat et al, 2011). This creates a discontinuous design flow, wherein the tools employed tend to be discrete rather than continuous.

While Building Information Modelling (BIM) gives architects, engineers, and contractors the insight and tools to plan, design, construct and manage buildings efficiently, there are limited and robust environmental tools that link into this platform. Consequently, when the design needs to be evaluated, the model is exported and detached from the design development process. By the time the model is ready to use for performance analysis the design has already evolved into something else. To avoid this, the design team waits until the design is frozen before sharing the model with the sustainability analysts – so that by the time the design has been analysed there is no time to make further changes. This process of modifying the design to achieve a set of performance criteria is inefficient (Azahar et al.) and

the workflow ends up being more about evaluating the design rather than informing and guiding its evolution.

Throughout the years, architects have come up with computational methods to assess the spaces they design. However, designers still tend to rely on rules of thumb that offer generic "environmental" design advice (Prat et al, 2011). This reflects a lack of training on the part of architects, a lack of incentives and even a lack of interest in learning about sustainable design (Hubers, 2011). We believe that the education system is catching up and that the standards and codes will help to achieve some degree of sustainability in buildings, but this has led to the widespread use of simulations to merely evaluate code and rating systems compliance (Prat et al, 2011).

This paper will present the current design workflow with its potential and challenges, as well as propose a new and more efficient workflow in integrating sustainability into the design process. This proposed workflow is supported by a set of parametric sustainability tools that will be explained through case studies.

## Context

One of the principal goals of sustainable design is to achieve optimum occupant comfort with the least possible amount of energy usage, but designers often forget that they produce buildings for people and to do this effectively they need to understand how the human body and mind work. Client's requirements and the building program, such as adjacency requirements, are used to drive the design of buildings, but climatic and energy driven functions are becoming part of the equation. To ensure visual, acoustic, and thermal comfort, designers can now use Building Performance Analysis (BPA), but how can we ensure that designers perform meaningful BPA at an early stage of the project and understand the environmental impact of their design decisions? Environmental tools have been out there for years now and research has been looking to integrate them into the design workflow, to ensure these tools can be more efficient in terms of time and effort, but the truth is that this has not yet been achieved. The Royal Institute of British Architects (RIBA) published green overlay guidelines in 2013 (Gething, 2011); but there have been no subsequent updates. The guidance does not offer practical solutions to improve design, but its fundamental contribution is in providing a holistic design methodology to streamline delivery, minimising the duplication of modelling effort and maintaining the design integrity.

Often, the environmental tools available employ standalone software, for which designers need to build a whole new model. Exporting and importing models sometimes works, but there is typically some tweaking required to simplify the model in order for the environmental software to read it properly. This second option can, sometimes, be even more time consuming than the first one. In the last years, we have also seen environmental plugins arising for 3D software that the architecture industry uses to design, such as Revit or Rhino, but these plugins can also have flaws and challenges, such as the ones exposed next.

Sefaira for Revit does an excellent job at being an intuitive tool with not much PC power required, but finds it challenging to read complex geometries and does not allow the designer to visualise the different iterations nor to translate them into the 3D design environment. On the bright side, working in the Revit platform can allow designers to integrate environmental parameters within the BIM, enabling collaboration between architects, engineers, and contractors, facilitating sustainable design. This is often referred to as Green BIM (Krygiel et al, 2008), but at the moment does not integrate any environmental simulation. At the same time, Ladybug and Honeybee for Grasshopper for Rhino are able to translate the different

iterations into the 3D design environment, making available the visualisation of different options, but these plugins are far from being intuitive and require the user to have specific skillsets. Also, the benefits of working in a platform like Grasshopper, a graphical algorithm editor, is that it allows for multi-objective optimisations and customisation of the analyses.

## Research

To ensure that designers perform meaningful BPA at an early stage of the project and understand the environmental impact of their design decisions, architects need a high dimensional design space that can be rapidly simulated, analysed, and visualised (Pratt, 2011). This research focuses on creating a pathway for better designs, on guiding designers working on a project to fully integrate sustainability into their workflow through a truly holistic approach.

## Workflow

During the research, a six step approach to sustainability was developed (Figure 1.). The goal of this methodology is to achieve measurable and sustainable performance in projects and practices, but also to persuade and guide designers rather than to dictate prescriptive solutions.



Figure 1. Six Steps approach to Sustainability.

The Six Steps follow the ‘London Plan’ message; **Be Lean**: use less energy, **Be Clean**: supply energy efficiently, **Be Green**: use on-site renewable energy. They are as follows:

1. *Discovery & Definition*: Focuses on the organisation of the team, identifying key roles and responsibilities and creating a collaborative framework. The brief is validated and the challenge is framed by establishing ambitious, yet realistic, sustainability targets with the design team and stakeholders.
2. *Climate & Place*: Focuses on the natural attributes that the site offers. The climate specifics are studied to better understand the needs of each space in relation to their environment and microclimate.
3. *Load Reduction*: Encourages exploring the passive and innovative methodologies to reduce the building loads. During this step, BIM and in-house parametric design tools help to track and improve the sustainability targets.
4. *Integrated solutions*: Identifies architectural and building services environmental strategies and systems, equipment and fittings that can function in an integrated, synergistic fashion with the passive strategies to achieve occupant comfort. Energy and water efficient measures should be integrated during this step.
5. *Renewable Systems*: Consider the integration of renewable and low carbon technologies for affordable and clean energy and possible synergies with wider energy strategies on a community level, which are directly linked with the active systems.
6. *Occupancy*: Designers’ sustainability engagement should not end when the building is completed. Human behaviour should be monitored and energy use tracked, to

understand whether or not the building performs according to the predicted energy use during the design stages. Post Occupancy Evaluation and adoption of Soft Landing principles will allow the team to modify the building performance through new operational targets, and understand how people respond to and use the completed facility and, linking back to *Step 1*, feed the collected data into future projects.

The Steps were overlaid with the RIBA plan of work (Figure 2), which defines the UK model for the building design and construction process. Through this, designers are able to relate appropriate actions to the relevant design stages.

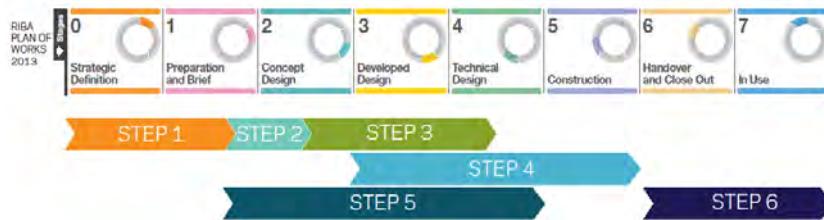


Figure 2. Six Steps approach overlaid with RIBA's timeline.

A central aspect of this project is the development of a sustainable design reference and brainstorm tools to go along with the Six Steps methodology to create a workflow. The aim is to provide a better understanding of how the concept of sustainable design can be more effectively integrated in the design practice.

### **Tools**

Sustainable design specialists cannot always analyse everything, given project time constraints and insufficient computing power, therefore they have to ask the right questions at the right moment. These set of in-house developed tools are meant to answer specific questions at different design stages throughout the Six Steps methodology, creating a proactive workflow that uses BPA to inform the design proactively rather than to evaluate it reactively. With this workflow, the design is provided with a framework to work towards.

The tools are developed in Grasshopper, using Ladybug and Honeybee components along with some personalised coding. This parametric design environment allows designers to generate a wide range of variations within a defined parameter keeping up with the continuous change of the dynamic model. At the same time, this graphical algorithm editor is linked to the 3D design environment of the architects' digital world. This link allows designers to rapidly create, simulate, and understand the trade-offs and benefits for each given option. In the same way the interface allows for parametric design, it also allows for parametric simulations through the developed tools providing rapid graphical troubleshooting, offering different options rather than specific answers. As the architectural model continues changing, the environmental model remains the same saving time and having full control of the decision making process within the design space. This setup allows for a smoother collaboration between designers and sustainable design analysts.

#### *Sustainability Analysis Tool*

This was the first tool that was developed and it is the only one that is based in Excel. It analyses EPW weather data graphically and informs the main passive strategies that correspond to climate analysis.

#### *Massing Optimisation*

Through a set of parametric simulations, this tool alters the given geometry though the defined free parameters aiming for the minimum or maximum overall solar radiation on the building itself, a neighbouring building, or an outdoor space.

### *Shading Evaluation*

Using a ray tracing approach, the tool either assesses an existing shading device and draws the cutting line for optimal performance based on sun vectors directly incident on the glazed surface, or creates an optimal extrusion to serve as a guideline for the design of the shading device.

### *Mesh Optimisation*

Once the pattern of the mesh is designed and the free parameters have been identified, the tool is able to output the optimal proportions of the pattern in order to minimise or maximise the incident solar radiation on the building envelope through a set of radiation analyses.

### *Outdoor Comfort*

This tool assesses the perceived temperature of a specific area taking climatic data and the built environment into consideration.

### *Louvres Optimisation*

Similarly to the Shading Evaluation Tool, this tool shows the trade-offs and benefits of different louvre systems.

### *Photovoltaic/Building Integrated Photovoltaic Energy Generation*

With a given geometry and its context, it is capable of, not only giving the energy output, but the relative potential efficiency of different systems for a more informed decision making.

It must be noted that the interface of the last six tools is not intuitive and a knowledge of basic grasshopper skills are required to use them effectively.

## **Case Studies**

The six steps methodology has been tested with projects of different scales and complexity. The tools were inspired by specific projects, but even though each project is specific, we found that often the same questions are asked during the design process. Therefore, we believe that the same workflow, using the Six Steps approach with the support of the sustainable parametric tools, can be applied to all of them.

### *Mesh Optimisation in Barcelona*

The studio was working on a competition for a Barcelona, Spain, based sports and entertainments building. The Mediterranean climate brought with it the hurdle of dynamism; no strategy should be static as the climate changes throughout the year and so should the building's response to it.

The building's envelope is the physical separator between the interior and the exterior environmental conditions, therefore our focus was on the arena's second skin. The design goal of this skin, a perforated metal sheet, was to restrict the summer unwanted heat gain while allowing the useful winter heat gain and daylight to penetrate the interior of the arena. This situation inspired the Mesh Optimisation Tool, to help define the pattern that would form this second skin. The tool first conveys a solar radiation analysis, as the designer determines the pattern for the mesh, its free parameters and boundaries. In this case, the pattern was a series of round perforations in the metal sheet that would vary in diameter. The boundaries were set to be a minimum diameter of 250mm and a maximum of 1500mm, with intervals of 250mm. Lastly, the pattern, along with its boundaries, are linked to the radiation analysis results for the tool to distribute the perforation diameters according to the solar radiation received on that portion of the metal sheet.

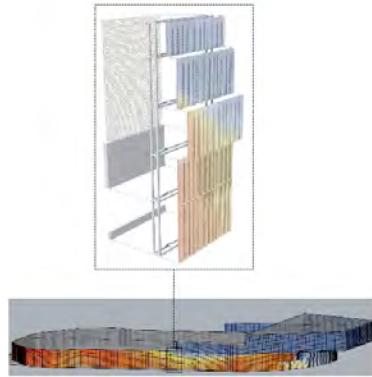


Figure 3. Detail of Responsive Mesh Pattern.

By using this tool the designer not only creates an interesting pattern, but the design of the mesh can adapt to design changes easily, as it will change accordingly if the designer modifies the building geometry. It can also be exported directly to the manufacturer. This tool can be applied to any mesh surface and optimise the pattern for a different output, such as solar angle to avoid glare or daylight availability.

#### ***Outdoor Comfort in Oman***

The underlying premise of the development was to create a well-balanced integrated mixed use residential and resort orientated community that includes a range of housing typologies, supported by mid to high end resorts which will be activated by the waterfront and cultural amenities. Due to the scale and of the project, outdoor comfort was the principle that guided the Concept Design Stage.

Ways to maximise wind flow and minimise solar radiation were explored along with evaporative cooling strategies, which inspired the Outdoor Comfort Tool. The designer identifies the area of study and sets up different scenarios, i.e. sunny without wind, shaded with wind, etc. In this case the scenarios were sunny with wind and shaded with wind (Figure 4). Eventually, the tool assesses the perceived temperature in each given point of the grid based on the climate and the microclimate that the build environment produces due to the given scenarios.

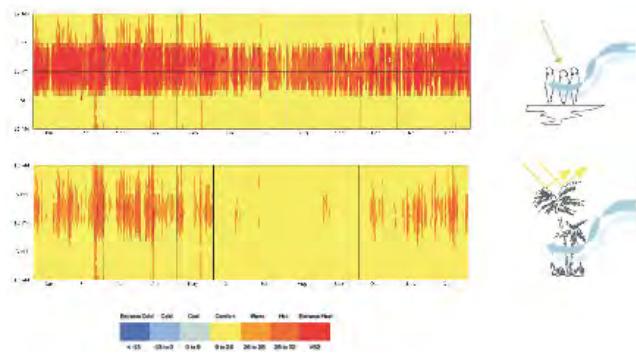


Figure 4. Annual Perceived Temperature.

The tool can identify what is the environmental need for each time of the year, as well as the specific location where these strategies are needed. This specific design achieved an improvement of 57% in the amount of hours that the outdoor environment is within comfort range through street orientation to encourage wind flow, self-shading streets and evapotranspiration through landscape.

### ***Shading Evaluation in Qatar***

The Commercial Boulevard's public realm was in need of improvement. There was a need to bring together an efficient transport network with the sense of high quality public pedestrian realm upon which successful outdoor shopping activities rely. For an environment of this nature, where temperatures are high and humidity low, the main challenge was designing an outdoor environment that provides optimal visitor well-being and comfort.

There was a need for a Geometry Optimisation Tool to help optimise the shading devices for plazas, platforms and waiting areas, ensuring the maximum hours of solar radiation protection with the minimum resources possible. Through raytracing, the tool identified where the cutting line should be in order to minimise the solar stress on the waiting areas of the platform.

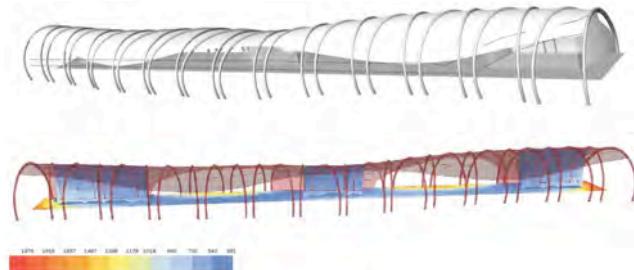


Figure 5. Light Rail Station Shading Optimisation.

For raytracing, the tool allows the designer to select the time of the year when the radiation must be avoided. Those vectors will then intersect with the context, or not. The vectors that do will be discarded, but the ones that do not, will continue until they intersect with the designed geometry. These intersection points draw a line into the architect's 3D environment which identifies where the optimum boundary of the shading device should be.

### ***Massing Optimisation in the United Arab Emirates***

One of the Rating System targets of this Arena District and associated retail was to reduce at least 20% of the annual external heat. Therefore, the lower the degree of solar radiation the geometry received, the less solar heat gain the building will experience. As sustainability specialists, we worked closely with the design team in the optimisation of the geometry, the skin, and the louvres. The Geometry Optimisation Tool was developed to inform the optimum tilt of the facades. In this specific project, the points touching the ground were set as the free parameters, having the freedom to move in the direction orthogonal to the façade in steps of 1m (Figure 6). Then, different iterations went through a radiation analysis - the tool uses this data to create a new iteration that should be closer to the goal, minimising solar radiation and increasing computing time efficiency. When the different iterations had been studied the results were ordered from the least to greatest incidental solar radiation, exposing the different geometries in the 3D design environment.

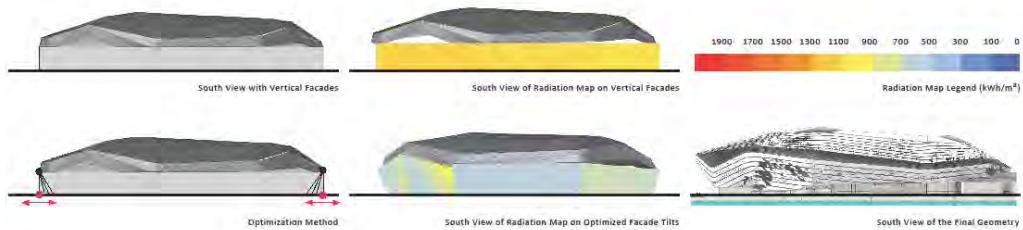


Figure 6. Geometry Optimisation.

The geometric alteration boundaries should respond to the minimum and maximum gross floor area, the programme requirements, etc. The tool aims to find a balance between the spatial and the environmental needs of the building, looking for the right solution and not the best for either criteria, exposing the trade-offs and benefits of each design iteration.

### **Occupancy**

The above mentioned case studies demonstrate our approach to evidence-based design. Step 6 'occupancy' requires continuous commitment from building owners, facility managers, users, and design consultants to monitor, strategise and implement green operations plan. HOK initiated an occupancy engagement programme for the Toronto-Dominion Centre in 2011. Without upgrading this 60' commercial tower, its energy usage was reduced by 40% through educating the occupants.

### **Conclusion**

The outcome of this design research addresses fundamental questions in sustainable design and provides practical toolkits for designers. Our case studies have found that this approach allows us to efficiently explore design options by rapidly simulating, analysing and visualising the results in a continuous workflow. Tracking design changes and the integration with BIM remains a challenge. Although the initial case studies that have been presented in this paper are all Rhino based, the method shows promise and has been proved useful for the sustainable design process. These tools should be further developed and integrated in Green BIM to achieve full collaboration and integration throughout the architectural discipline. As a next step for development, some of the tools could also explore multi objective optimisation. It will help where optimal decisions need to be taken in the presence of the trade-offs between two or more conflicting objectives, such as maximising daylight while minimising solar heat gains.

The result of this research will prompt some deep changes in design organisations on how they approach evidence - based design. It will contribute to the knowledge of a holistic design process based on a detailed account of key factors underpinning the behavioural intentions of architects to adopt BPA in the early design stages. For these reasons, we believe that architects will engage with this proactive process, particularly those who believe that sustainability is part of the architectural equation and look for a smooth collaborative effort between all the different functions that contribute to it.

### **References**

- Aksamija, A.; Guttman, M.; Rangatajan, H.; Meador, T. (2001). Parametric Control of BIM Elements for Sustainable Design in Revit: Linking Design and Analytical Software Applications through Customisation. *Perkins+Will Research Journal*, 03(01), pp. 32-45.
- Azhar, S.; Brown, J.; Farooqui, R. *BIM-based Sustainability Analysis: An Evaluation of Building Performance Analysis Software*. Auburn University; Florida International University.
- Gething, B. (2011). *Green Overlay to the RIBA Outline Plan of Work*. London: RIBA Publishing.
- Hubers, H. (2011). Collaborative design of parametric sustainable architecture. In: *Management and Innovation for a Sustainable Build Environment*, Amsterdam, The Netherlands, 20 – 23 June 2011.
- Krygiel, E.; Nies, B. (2008). *Green BIM: Successful Sustainable Design with Building Information Modelling*. Indianapolis: Wiley Publishing, Inc.
- Pratt, K.; Bosworth D. (2011). A Method for design and analysis of parametric building energy models. In: *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, Australia, 14 – 16 November 2011.
- Sala, S.; Ciuffo, B.; Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, 119(2015), pp. 314-325.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **The impact of imposed façade design on the occupants' visual and thermal satisfaction in educational buildings in Jordan: The case study of the German Jordanian University in evaluating the performance of Architecture**

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**Abstract:** Nowadays educational buildings in Jordan are facing a major challenge with the users' satisfaction, in terms of thermal and visual comfort, having become completely sealed environments. There is a major dissatisfaction from overheating in the cold period and very cold indoor environments in the hot period. In addition, uncontrolled sun access is becoming a common issue in the recent trend of glazed facades in such typology. This research paper will analyse and discuss the impact of such façade design based on user satisfaction. The research paper will take the German Jordanian University-Madaba, Jordan as a case study for the fieldwork to analyse and evaluate the occupants' satisfaction through quantitative and qualitative analysis. The findings of the research will serve as a reference for Educational Building Design Guidelines; the first of its kind in Jordan.

**Keywords:** Educational Building, Façade Design, Comfort, Building Performance, Hot Arid Climate.

### **Introduction**

Educational institutions in Jordan are becoming fully sealed buildings to provide thermal comfort for their large number of users with diverse needs. The resulting heavy reliance on mechanical systems of these new educational buildings is viewed as a reflection of their prestigious status (Mechanical Engineering Department, 2016). This trend is observed globally, where Nicol et al (2012) stated that architectural profession is giving engineers the responsibility of providing comfortable adaptable spaces in their buildings, ultimately resulting in more buildings which are fully dependent on mechanical systems. Yet, high dissatisfaction with indoor thermal comfort is very common across sealed buildings; and complaints include overheating in the cold period, and very cold indoor environments in the warm period (Nicol et al, 2012).

This research paper analyses and highlights the impact of imposed mechanically controlled classrooms and façade design on students in educational buildings, taking the German Jordanian University in Madaba, Jordan, as a case study. This paper aims to draw attention to the effect of such sealed environment on the users' interaction with the building, and emphasises the preferred adaptive opportunities undertaken by the students in a measured hot week of July 2016, in which the fieldwork took place.

This paper is part of a comprehensive analysis and performance evaluation of the main university building (Building C). The analysis in this research paper includes studying

two classrooms, by installing data loggers, taking spot measurements, and interviews with the occupants.

### Case Study of German Jordanian University

#### Climate

The German Jordanian University (GJU) is located in Mushaqar in the Madaba Governorate 31.7° N, 35.8° E (German Jordanian University, 2014). Madaba is located in the west of Jordan, and has a hot arid climate (see Fig. 1). The climate data was generated with Meteonorm global meteorological database 7.1, an interpolated weather station. Figure 1 illustrates the average monthly mean, minimum and maximum dry bulb temperatures, combined with monthly average solar radiation and wind speed.

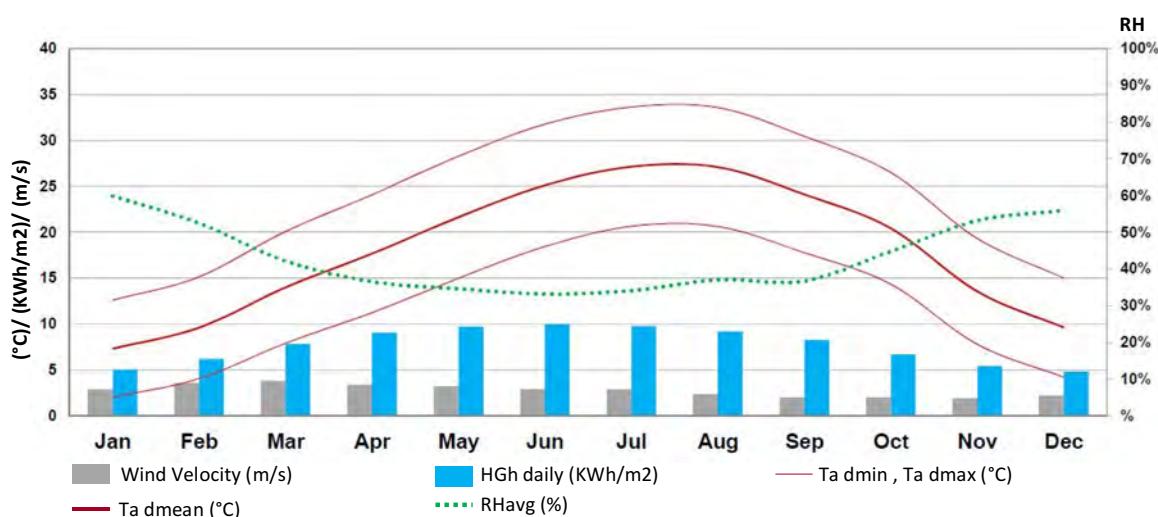


Figure 1. Monthly Mean, Minimum, Maximum dry bulb temperatures for Madaba.

Madaba is subject to intense solar radiation throughout the year. The warm period is between June and September, and the maximum average temperature exceeds 30°C. The moderate period is between March and May, and the maximum average temperature ranges between 18-20°C where buildings can be coupled with the outdoors. The cold period is between December and February, during which the temperatures can drop to zero. Madaba has a hot dry climate with large daily temperature swings between day and night. This diurnal temperature swing of 12K provides great potential for nocturnal cooling (Givoni, 1994) that can be effective during the mild and warm period as a passive cooling strategy.

The research was completed in the warm period, during GJU's summer academic term, which starts in June and lasts until late August. The spring term, between September and November, is considered moderate and is the period the building is fully occupied. Moreover, the winter term lasts from December to February.

#### GJU Design Concept

The GJU was designed by Dar Omran Architects in Amman, Jordan. The concept was to combine the German and Jordanian cultures in one urban context. The interaction between both cultures is illustrated by bridging two wings with a transparent bridge structure to emphasise the connection between the cultures (Dar Al-Omran, 2014). Figure 2 shows the full campus of GJU where all the buildings reflect the concept form.



Figure 2. Campus of the German Jordanian University.  
(Source: Dar Al-Omran, 2014)



Figure 3. Panorama of Building C, GJU.

The campus buildings were designed to have dynamic facades (see Fig. 3), to reflect the continuous evolution and growth between the two cultures (GJU Site Architect, 2016). The fieldwork was conducted in the main building, Building C. Shown in Fig. 3 key plan, Building C is the School of Natural Resources Engineering and Management.

### Methodology

Building C has a completely sealed environment, relying on mechanical systems throughout the whole year. The heating is turned on starting December until the end of April, and the air conditioning starts from May to October (Building Management Office, 2016). Two typical classrooms were selected in the southern wing of Building C for this analysis – southern classroom C232, and northern classroom C231 – are illustrated in Figs 4 & 5 respectively. Each Classroom is 10.5 meters in length and 5.5 meters in width with a clear height of 2.8 meters. Figure 4 and 5 show the impact of the irregular window distribution reflecting the design concept mentioned earlier.

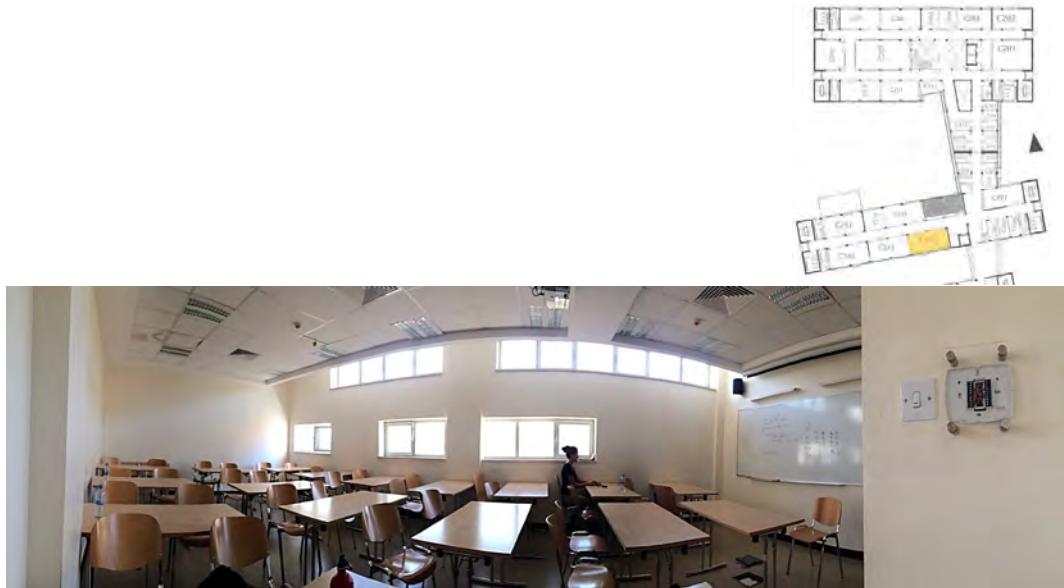


Figure 4. Southern Classroom C232 showing the damaged AC Control.



Figure 5. Northern Classroom C231 showing the covered AC Control.

The measurements were completed during a typical week in the hot period. Two data loggers were installed over a period of 10 days from the 26<sup>th</sup> of July to the 8<sup>th</sup> of August 2016 in both classrooms. Additionally, spot measurements were taken during that week, and interviews were conducted with a sample of the students. Both data loggers were placed in the same position in both classrooms; hung from the ceiling. The readings were used to compare the occupied classrooms and observe the impact orientation has on the two sealed classrooms. The air conditioning system in the building was set at 21°C by the Building Management Office (2016) during the working days from Sunday to Thursday. The system is automatically turned on and off from 7:00 AM until 3:30 PM.

## **Analysis**

### ***Occupancy and Performance***

Graph 6 illustrates the combined results from the data loggers for the southern C232 and northern C231 classrooms. Both classrooms were occupied between 8:30 AM and 3:30 PM. The average number of students in each classroom was 15 students. As portrayed in Fig. 6, there was a constant 2-3k difference in the ambient temperature between the classrooms during occupied days and during the free running weekend; which is the result of the different orientations.

The most interesting finding was the students' adaptive behaviour in both classrooms. Students preferred to couple with the outdoors, as they found it more comfortable and satisfying when they had a pleasant breeze from the few operable windows in each classroom. Students preferred higher ambient temperatures with a breeze than the set cooler temperature of the mechanical system. Their main goal was to ventilate the classroom and get fresh air in, and even opened classroom doors to create a draught. As shown in Fig. 6, students are constantly coupling with the outdoors and raising the indoor ambient temperature of classroom C232 to 27°C during occupied hours. This is aligned with Givoni (1998) that people in the hot arid region can handle higher temperatures when air movement is available.

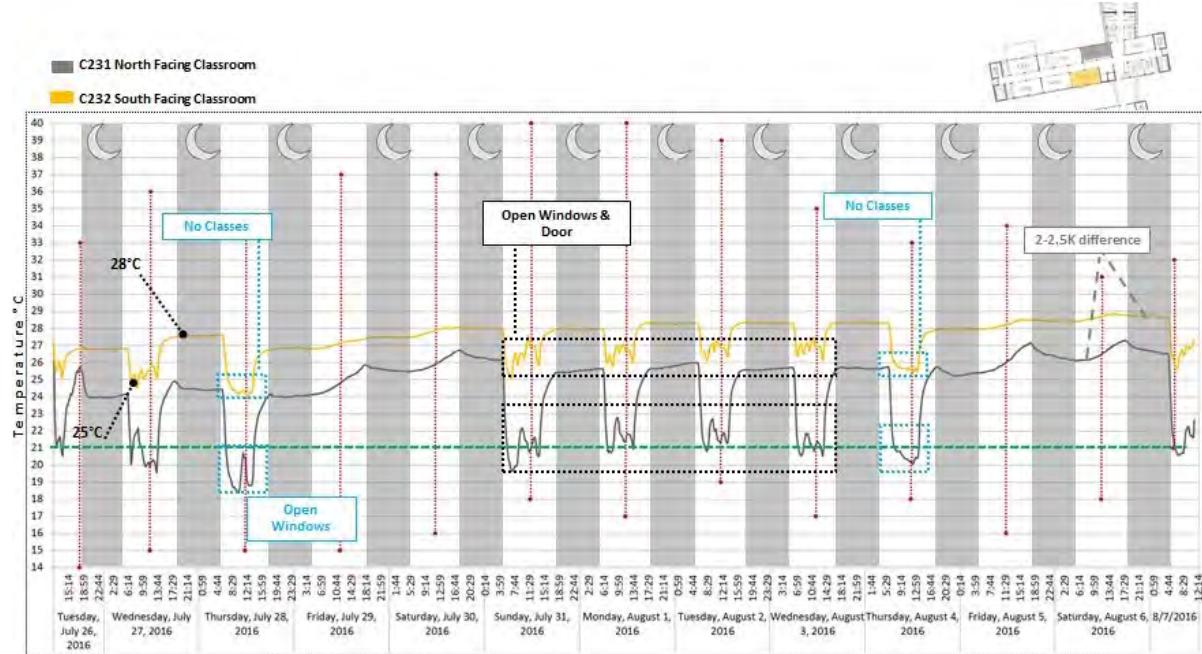


Figure 6. Data Logger readings for Northern C231, Southern C232 classrooms.

Based on the comparison of the ambient temperatures in both classrooms, the building was found to be effective in terms of sheltering from the harsh outdoor environment both on free running and occupied days. Figure 7 shows that during free running days, the indoor temperature was very constant and did not follow the outdoors in any way, where the ambient temperature was recorded around 26°C while the external high and low temperatures for those days were recorded at 37°C and 16°C. Hence, the building envelope was acting as an effective thermal mass. Also, the graph draws attention to the adaptive behaviour of the students on Sunday the 31<sup>st</sup> of July, opening the operable windows and doors, raising temperatures to reach the free running passive environment levels. This is clear from the fluctuations in the lines during occupied hours. It is worth noting that classroom C232 was not occupied on Thursday the 28<sup>th</sup> of July, showing a relatively smooth graph.

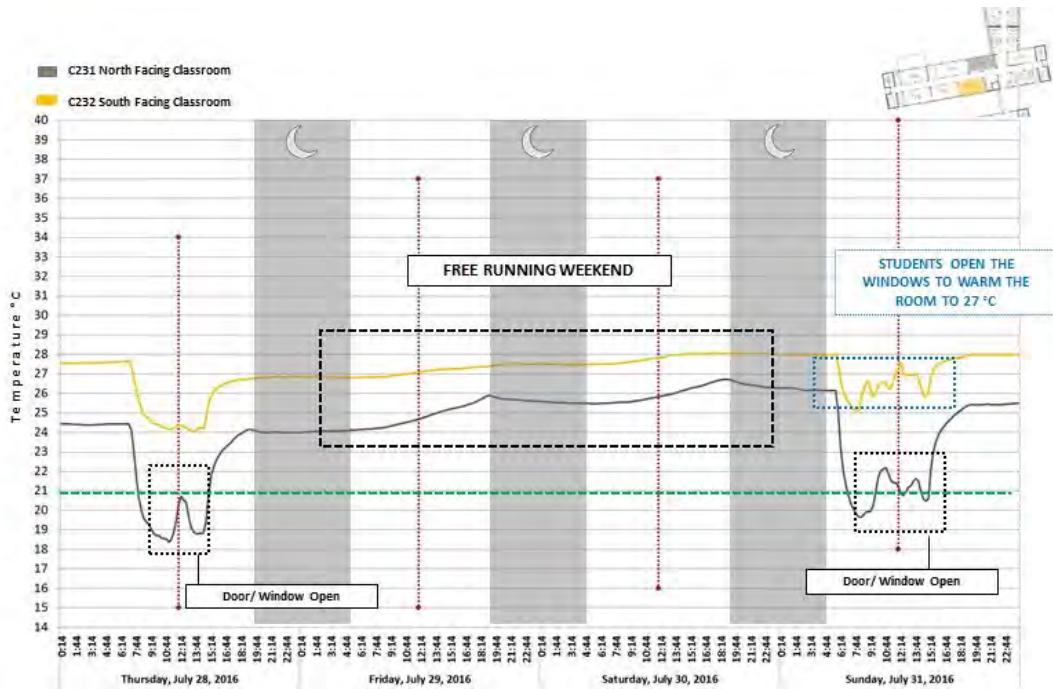


Figure 7. Data logger readings for C231 & C232 comparing free running days vs. occupied days.

Figure 8 illustrates the desired internal environment created by the students in classroom C232 on the 26<sup>th</sup> of July. The indoor air temperature measured was 27.9°C while the outdoor was 32°C. The AC vent surface temperature was 18°C, the walls around 21°C. All reachable/operable windows were open; the pleasant breeze was measured at 0.4-0.6m/s.



Figure 8. Spot measurements taken in classroom C232.

### Façade design

Figure 9 displays the illuminance level measured in both classrooms C232 and C231 where the horizontal outdoor illuminance was measured to be 104 000lx outside of classroom C232 and 6800lx outside of classroom C231.

The figure highlights the irregular distribution of the indoor horizontal illuminance at some task areas across the classroom. This behaviour was found in all measured classrooms due to the irregular window distribution in the design concept of the façade. This also resulted in disadvantaged places in the classroom in terms of view of the outdoors. The

noticeably small indoor to outdoor illuminance ratio of the classrooms is an outcome of the windows' measured low visible light transmittance (VLT).

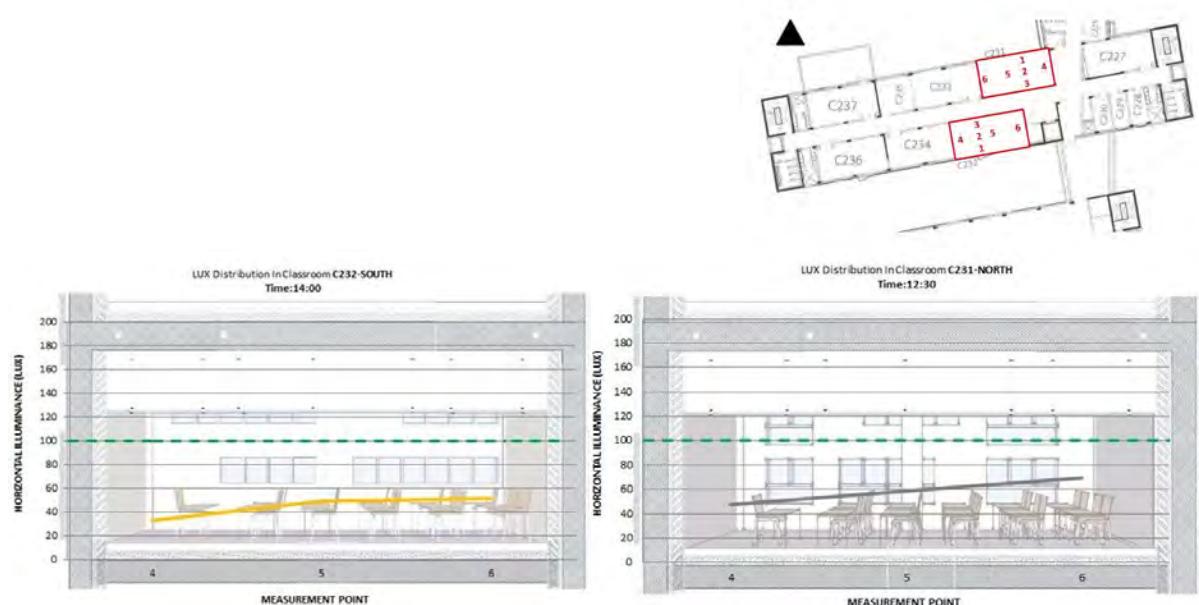


Figure 9. Illuminance spot measurements in both classrooms.

## ***Orientation***

When the horizontal illuminance were measured while artificial lights were off, both north and south facing classrooms show very little natural light access which does not exceed the 100 lux value; one fifth of the desired value for task areas illuminance in educational buildings. These results explain the 100% reliance on artificial light during the day, which was affirmed by all the students when asked if lights were always on. This low, uncontrolled accessibility of daylight is a result of very low VLT of windows; a specification chosen by the mechanical engineers (Mechanical Engineering Department, 2016).

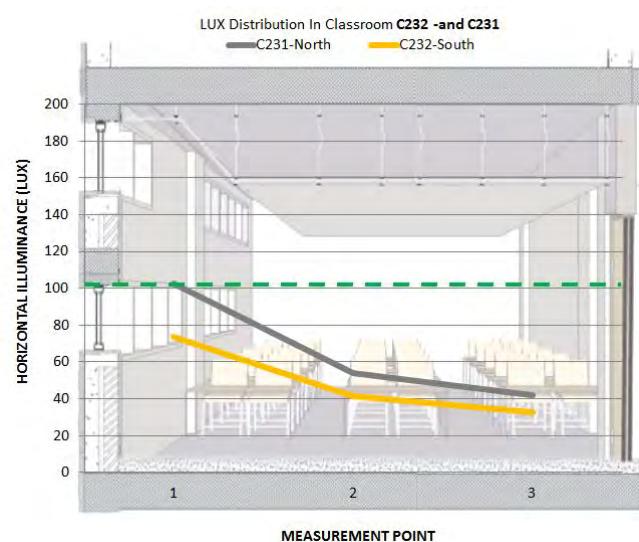


Figure 10. Illuminance spot measurements comparing C231 & C232.

This confirms Nicol's statement of the ever-growing trend of giving such design decisions to engineers where they determine the shading coefficient and window type according to their mechanical systems' needs.

## Conclusion

The study highlights the importance of designing for the user at the outset, and allowing for adaptive strategies in educational buildings. Contrary to growing belief in Jordan that mechanically controlled buildings are prestigious and offer a superior occupant experience, the study portrays a high need for adaptive opportunities for the user. While an automated mechanical system imposed an uncomfortable environment, it prompted the students to open classroom windows and doors in order to utilize natural ventilation as a passive strategy to reach comfort.

Additionally, the study reflects the need for conscious concept design at an early stage, taking into consideration the building's orientation, façade design and expected energy consumption levels. Although the dynamic façade design created a strong visual connection with the outdoors, its impact on daylight distribution within classrooms was not prioritised, resulting in constant reliance on artificial lights. In conclusion, adaptive opportunities are always preferred and needed to create healthy and more productive internal environments, especially in educational buildings.

## Acknowledgements

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## References

- Dar Al Omran, (2014). *Experience* [Online] Available at: <<http://www.daralomran.com/portfolio-items/german-jordanian-university/?lang=en>>.
- CIBSE (2006). Environmental Design. Guide A, 7th Edition. Chartered Institution of Building Services Engineers, London.
- German Jordanian University, (2014) *About the University* (online) Available at: <http://www.gju.edu.jo/content/about-gju-687>.
- Givoni, B. (1994). Passive and Low Energy Cooling of Buildings. John Wiley, & Sons, New York.
- Givoni, B. (1998). Climate Considerations in Building and Urban Design. John Wiley & Sons, New York.
- Nicol, F. et al (2012). Adaptive Thermal Comfort Principles and Practice, Routledge.

## Personal Conversations

- Building Management office (2016). Building C management and implemented system [interview] (Private Conversation on the 24<sup>rd</sup> July 2016).
- GJU Site Architect (2016). GJU Concept and Design [interview] (Private Conversation on 15<sup>th</sup> July 2016).
- Mechanical Engineering Department (2016). GJU vision and design criteria [interview] (Private conversation on the 22<sup>nd</sup> July 2016).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Thermal and Energy Audits in Existing Wineries. A Case Study

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**Abstract:** In wineries, energy flux exchange and thermal inertia are crucial for achieving constant temperatures. Primitive wineries were underground and interior temperatures stabilized at the site mean annual temperature. In Mendoza, Argentina, by the year 1600 buildings started to be built on-the-ground with traditional materials: adobe walls (raw earth blocks) and Spanish cane (*arundo donax*) with compacted mould roofs. Grape juices were exposed to temperatures over 25°C. A first reduction in the thermal resistance of the envelope occurred (if compared with a subterranean winery, at stable 16.5°C). As the use of energy consuming equipment for thermal conditioning generalized, new wineries started to be built with thin concrete slabs walls and galvanized steel roofs. A second reduction in the thermal resistance of the envelope occurred. Without auxiliary energy, interior temperatures during daytime in summer can reach 35°C. The objectives of this paper are: 1) to analyze materiality, thermal inertia and energy flux exchange of traditional and new envelopes, 2) to define critical control points of the wine making process and to perform a thermal and energy audit of a case study that presents both types of envelopes, and 3) to compare the obtained results with a case of an underground cellar.

**Keywords:** envelope, underground, on-the-ground, materiality.

### Introduction

Primitive wineries were caves where interior temperatures stabilize at mean annual temperature of the site. Even though in a winery energy flux exchange and thermal inertia of the envelope are crucial due to the constant need for stabilized temperatures, when first on-the-ground wineries were built, the creation of the empty interior space in the most economical way many times neglected the full structure of thermal mass resistance. And therefore, the problem of interior temperature variations in wine production began.

Grapes grow mainly between parallels 40° and 50° North Latitude and between parallels 30° and 40° South Latitude. 'Cuyo Region' in Argentina, especially the province of Mendoza, is located between parallels 30° and 35° South Latitude. This region climate is temperate continental with important daily and seasonal temperature variations and high heliophany. These climatic characteristics provide grapes of exceptional quality, but, at the same time represent a main constraint in the constructive aspects of a winery. An abrupt temperature change can put the whole wine production process in jeopardize. In Mendoza, Argentina, first wineries were documented in the year 1600, buildings were simple and almost without measures of protection and conservation of grape fruits. Small and middle size spaces on the ground. It is supposed that grape juices exposed to temperatures over 25°C corrupted rapidly and therefore, Mendoza's wines were of poor quality and easy

alteration of initial properties. (Rivera Medina, A. M., 1987) These first envelopes on-the-ground where built with traditional materials a first reduction in the thermal resistance of the envelope occurred (if compared with a subterranean winery, at stable 16.5°C).

Nowadays, the province of Mendoza is famous for its excellent wine and produces one of the best D.O.C. Malbec varietal (Fanzone et al., 2010). In order to provide stabilized low temperatures to produce such an excellent product, mechanical energy consuming systems like serpentine pipes inside tanks controlled temperature during the fermentation process; and air conditioned equipment were installed in oak breeding barrels rooms. As the use of energy consuming mechanical conditioning of spaces generalized, wineries started to present new envelopes that reduced drastically their thickness by using concrete slabs and galvanized steel in walls and roofs. Without the use of mechanical equipment, interior temperatures during daytime in summer can reach 30°C to 35°C, been very close to exterior temperatures. A second reduction in the thermal resistance of the envelope occurred.

This industrial activity based in the use of non-renewable conventional energy impacts in the environment through CO<sub>2</sub> emissions that contribute to global warming. In the case of the wine industry, wineries are located near or within the productive areas, which are very small oasis in the case of Mendoza. With their construction and operation, wineries affect on site the oasis microclimatic conditions. This impact can alter grape production compromising the continuity of the wine industry in the region.

To better understand the implications of the changes suffered in the envelopes of wineries over the time, the objectives of this paper are: 1) to analyze materiality, thermal inertia and energy flux exchange of traditional and new envelopes, 2) to define critical control points of the wine making process and to perform a thermal and energy audit of a case study that presents both types of envelopes, and 3) to compare the obtained results with a case of an underground cellar.

## **Case Study**

### **Climate and site**

Winery A is situated in the North Oasis in the Province of Mendoza, Argentina, near the Andes Mountains (32°52'South Latitude, 68°51'West Longitude, altitude 750 metres over sea level). Mendoza has a continental dry-temperate climate with hot summers and cold winters. In summer, mean highest air temperature are between 35°C and 40°C, and lowest mean temperatures vary between 18°C and 22°C. In winter mean minimum air temperatures are bellow 0°C and mean maximum are between 10°C and 15°C. Global Horizontal Radiation vary between 24000 and 25700 kJ/m<sup>2</sup> in summer, between 14000 and 22700 kJ/m<sup>2</sup> in autumn and spring and between 9000 and 11000 kJ/m<sup>2</sup> in winter. Annually average of Global Horizontal Radiation is approximate to 18000 kJ/m<sup>2</sup>, been 700 W/m<sup>2</sup> as the highest power at solar noon. Losses by long wave radiation are approximate to 180 W/m<sup>2</sup>. Mean daily temperature differences reach 10°C to 18°C.

### **Materiality**

Winery A presents two types of envelope materiality: one traditional, mainly adobe walls (raw earth blocks) buried 1 meter in the ground and tile roofs with wooden structure, a mixture of Spanish cane (*arundo donax*) and mould as insulation; and one new, with metallic structure and galvanized steel walls and roofs. Walls present a concrete slab base, only roofs are insulated with polyurethane foam.

The difference in the envelope materiality responds to the decade of construction. The traditional envelope responds to the type of construction of the beginning of the 20<sup>th</sup> century. The new envelope is being built nowadays, mainly for bottling and storage phases, as the winery's production has increased and fermentation and breeding stages occupy the initial building. The choice of a new envelope responds to economical reasons as it is faster, cleaner and cheaper than the traditional one.

This type of materiality for the new construction is chosen even though executive engineers know for a fact that the winery performs better with the traditional envelope. Energy costs in Argentina are still very low (USD 0.15 per kWh) and therefore it is cheaper and easier to buy a new chiller for the new space than to built in the traditional way. That is why it is very important to propose solutions that attend the requirements of fast assembly with pre-fabricated materials.

Table 1 present physical properties of the materials used in the two types of envelope described. The U value, -that depends of the particular thickness used in the building-, is a very clear indicator of the great variety of energy flux exchanges that the envelope is going through in each space.

Table 1. Materials' properties. Sources: Incropera and De Witt, 1981. \*Esteves, Ganem et al., 2003.

	$\rho =$ <b>Density</b> (Kg/m <sup>3</sup> )	$C_p =$ <b>Specific Heat</b> (J/Kg.K)	$\lambda =$ Thermal <b>Conductivity</b> (W/m.K)	$e =$ <b>Thickness</b> (m)	$R =$ Thermal <b>Resistance</b> (m <sup>2</sup> .K/W)	<b>U or Heat Transmittance</b> (W/m <sup>2</sup> .K)
<b>Earth</b>	1800	1460	2.10	1.00	0.47	2.12
<b>Adobe</b>	1600	650	0.81	0.50	0.61	1.63
<b>Arundo donax*/mould</b>	75	1000	0.20	0.20	0.50	2.00
<b>Tiles</b>	1300	840	0.49	0.05	0.10	10.00
<b>Concrete Slabs</b>	2400	805	1.63	0.100	0.0600	1.66
<b>Galvanized Steel</b>	7850	460	45.00	0.005	0.0001	10000.00
<b>Polyurethane Foam</b>	49	1400	0.02	0.030	1.4200	0.70

### **Heat flux exchange**

In the traditional building of Winery A, 85% of the envelope is exposed to the exterior and therefore is located over the surface, and 15% of the envelope is buried in the ground. This subterranean percentage responds to differences in the ground that where maintained when the winery was built. In the case of new construction, buildings are constructed entirely over the ground surface.

Possibilities of self-regulation are evaluated from the comparison of the heat flux of the two cases by using Fouriers Law Equation (Eq. 1).

$$Q = U * S * (T_e - T_i) \quad (1)$$

Where:

Q = flux (W)

U = heat transmission coefficient (W/m<sup>2</sup>.K)

S = Envelope surface (m<sup>2</sup>)

T<sub>e</sub> = Exterior temperature (K)

T<sub>i</sub> = Interior temperature (K)

To calculate energy fluxes for the two types of space and compare their possibilities of self-climatic regulation, there will be established two fixed parameters: S = Envelope surface

= 100 m<sup>2</sup> and  $\Delta T$  (Te – Ti) = 10 K. The obtained results which show a tendency of the amount of energy flux that will be exchanged are shown in Table 2.

Table 2. Energy flux exchange in both types of envelope. Source: author's own.

	TRADITIONAL	NEW
WALLS	$Q = 1,630 \text{ W}$ ;	$Q = 10,000,000 \text{ W}$
ROOFS	$Q = 2,000 \text{ W}$	$Q = 700 \text{ W}$

Notice that exchange values are similar in walls and roofs in the traditional envelope and very different in the new envelope. Insulation of the galvanized steel makes an important difference, as this value is also lower than the ones obtained in the traditional envelope. For energy exchange analysis it is crucial that every element of the envelope is insulated no matter if its construction is traditional or new, constructed on site or pre-fabricated. Nevertheless, there will be important differences in these two envelopes when taking into account inertial benefits in a temperate continental climate with high variations between day and night and between seasons.

### **Thermal Inertia**

Thermal inertia calculus were performed with “Eduardo Torroja Institut Equations” (Eq. 1 and 2) using data provided in Tables 2 and 3.

$$I = R * S_{24} \quad (2)$$

$$S_{24} = 8.48 * 10^{-3} * \sqrt{(\lambda * \rho * C_p)} \quad (3)$$

Where:

I = thermal inertia adimensional parameter

R = thermal resistivity (thickness “e” /  $\frac{1}{\lambda}$ ) (m<sup>2</sup>.K/W)

S<sub>24</sub> = twenty four hour factor

C<sub>p</sub> = specific heat at a constant pressure (J/ kg.K)

ρ = material density (kg/m<sup>3</sup>)

λ = thermal conductivity (W/m.K)

Thermal inertia of the different materials that compose the heavy old envelope and the new envelope are shown in Table 3.

Table 3. Thermal inertia of the different materials that compose both types of envelope. Source: author's own.

	WALLS		ROOFS	
	Earth (1m thickness)	Adobe (0.50 m thickness)	arundo donax /mould (0.5 m thickness)	tile (0.05 m thickness)
TRADITIONAL ENVELOPE	94.86	38.91	10.38	6.32
	Concrete Slabs (0.10 m thickness)	Galvanized Steel (0.005 thickness)	Polyurethane Foam (0.03 m thickness)	Galvanized Steel (0.005 thickness)
NEW ENVELOPE	9.23	0.12	10.38	0.12

In this case, heavy envelope provides internal spaces with a crucial property: thermal stability. New envelope does not have the same possibilities. Up to this point there has been performed a complete envelope analysis using theoretical methods to evaluate the performance of Winery A. The next step is to perform *in situ* temperature measurements to perform a thermal audit.

## Thermal and energy audit

### Critical control points determination

Hazard Analysis and Critical Control Points (HACCP) IRAM 14104 (2001) a food safety methodology was adapted ad hoc to specific environmental and energetic issues concerning wine production. The winery has already certified the following food harmlessness policies: IRAM BMP (Manufacture good practices), HACCP (Hazard Analysis and Critical Control Points) and BRC (highest level): British Retail Consortium Standard Approval.

Therefore, HACCP methodology was already known and accepted by the management of the winery and it was possible to adapt it to environmental and energetic purposes. Consequently, in this study critical control points determine the specific moments in which temperature is essential to the final quality of wine. Environmental and energetic critical control points (CCP) were detected through a flux diagram in the industrial process. Figure 1 presents the flux diagram with photographs of the architectural spaces in each CCP.

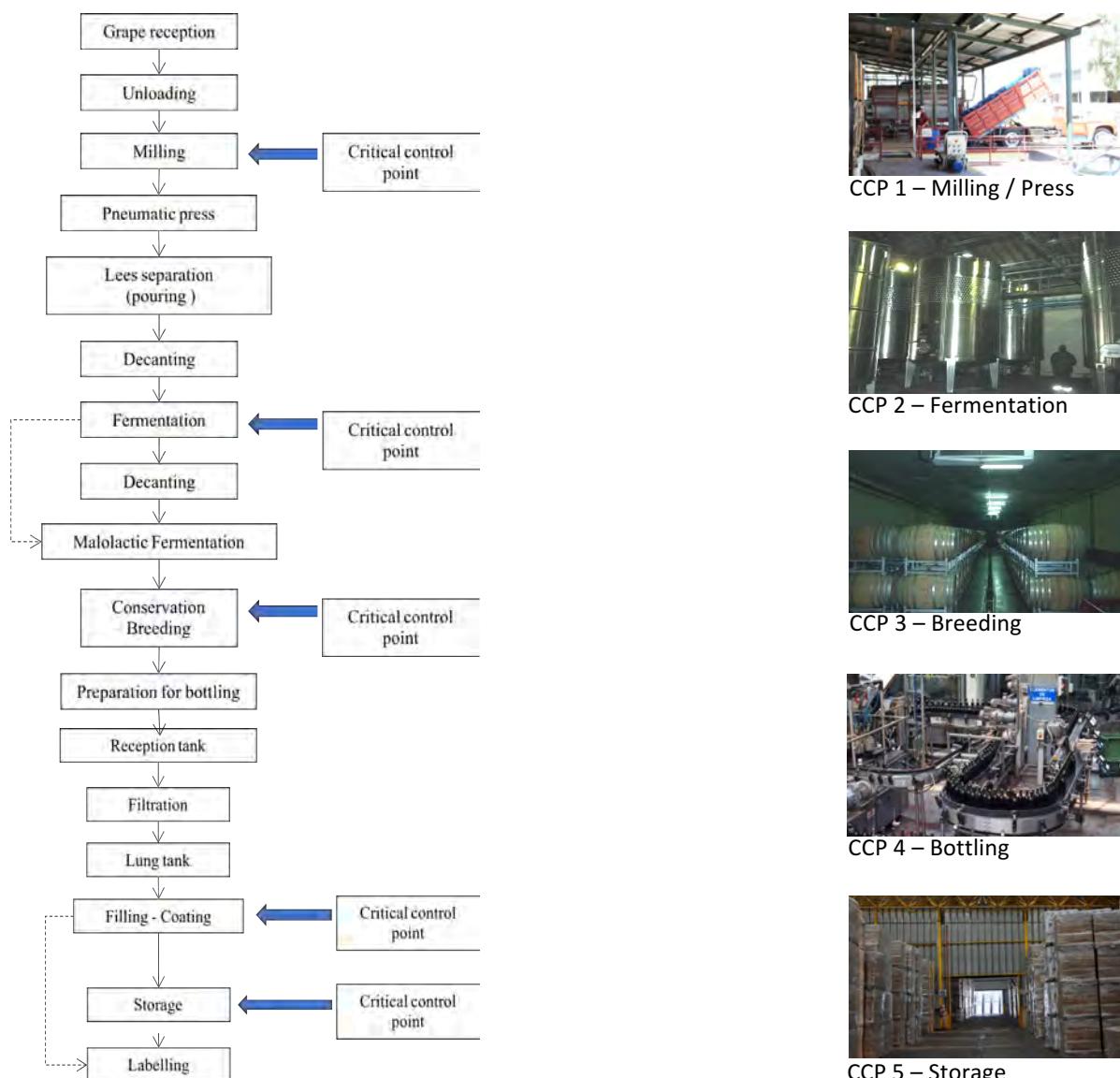


Figure 1. Flux diagram of the industrial process. Detection of thermal and energy critical control points (CCP). Source: author's own.

### ***Summer in situ temperature measurements (walkabout)***

Temperature measurements were performed following the five identified critical control points. A sixth control point was taken in the exterior in order to evaluate the envelope performance.

To perform in situ temperature measurements, the Walkabout methodology (Guerra, 2003) was used. This method is adapted to field trips in which it is difficult to set data loggers for a long period of time in all critical points. It consists mainly in taking several measurements of each space in a short period of time. For air temperature measurements an ONSET HOBO U14-001 data logger was used. It was programmed to take a measurement every 15 seconds in order to register air temperature while walking through the different spaces of the winery. Measurements were performed on January 13th, 20th, and 27th (summer in the South Hemisphere) at solar noon and the complete field trip took an hour. Table 4 shows the mean collected data for each CCP.

The Walkabout methodology was complemented with temperature measurements with ONSET HOBO U12 data loggers every 15 minutes for 20 days periods a representative space of the traditional construction (CCP 3 - Breeding) and a representative space in the new construction (CCP 5 - Storage). Management of data loggers followed the recommendations of Longobardi and Hancock (2000) for an efficient use of these instruments. (see Figure 2)

Table 4. Measured mean air temperature on each critical control point (CCP). Source: author's own.

<b>Measured critical control points</b>	<b>Air Temperature</b>
CCP 1 - Milling / Pneumatic press	31.5 °C
CCP 2 - Fermentation – Metallic Tanks	25 °C
CCP 3 - Breeding – Oak Barrels	25 °C
CCP 4 - Bottling (filling/coating)	32 °C
CCP 5- Storage	30 °C
CCP 6 – Exterior	35 °C

### ***Auxiliary energy requirements***

Grapes arrive at a mean temperature of 26°C, and temperature has to drop to 8°C after undergoing the press and the first cooling serpentine. Subsequently, in metallic double-skinned tanks juices' temperature has to be stabilized at -5°C. If we take into account that measured air temperature in the press is usually over 33°C and 25°C in the location of metallic double-skinned tanks, the  $\Delta T$  is 25°C in the first case and 30°C in the second case. These temperature differences make the use of chillers so intensive, and therefore the use of auxiliary energy.

Winery A has three chillers: one of 500.000 B.T.U./hour, and two of 300.000 B.T.U./hour, for a total of 1.100.00 B.T.U./hour. All year long 500.000 B.T.U./hour (1 chiller) are used for breeding and bottling. Four months a year, during fermentation, the amount of B.T.U./hour increases to 1.100.000 (3 chillers) to stabilize the fermentation process of 1.500.000 of liters.

### ***On-the-ground and underground thermal comparison.***

To better understand the implications of the changes suffered in the envelopes of wineries over the time, it is presented a comparison of the obtained results of the two representative spaces (traditional and new construction) in Winery A with a case of an underground cellar.

Air temperature measurements with ONSET HOBO U12 data loggers were performed for a week at the same time (January 20th to January 26th) in three different interior spaces, and in the exterior:

- 1) The space in Winery A identified with the critical point 3 corresponding to Breeding within a traditional envelope.
- 2) The space identified with the critical point 5 corresponding to Storage within a new envelope.
- 3) The underground cellar
- 4) The exterior

Figure 2 shows the measured data. Exterior temperatures vary from 14°C to 31°C with daily variations of 15°C. Notice that temperatures in new envelopes are closer to the exterior ones (between 17°C and 27°C) during daytime and also during night time, with daily variations of 10°C, making noticeable the lack of thermal inertia and mass in the envelope. In traditional envelopes temperatures present daily variations of 4°C and range from 20°C to 24°C. In this case thermal inertia and material properties combine to keep interior temperatures 11°C bellow exterior ones during daytime, but also 6°C over exterior temperatures at night time.

And, the subterranean cellar presents temperatures almost stable at 18°C with no daily variations. As the cellar is not completely buried 2 meters underground, temperatures are between 1.5°C and 2°C higher than the annual mean air temperatures of the site. Nevertheless, these are excellent temperatures for wine breeding without any kind of energy consumption.

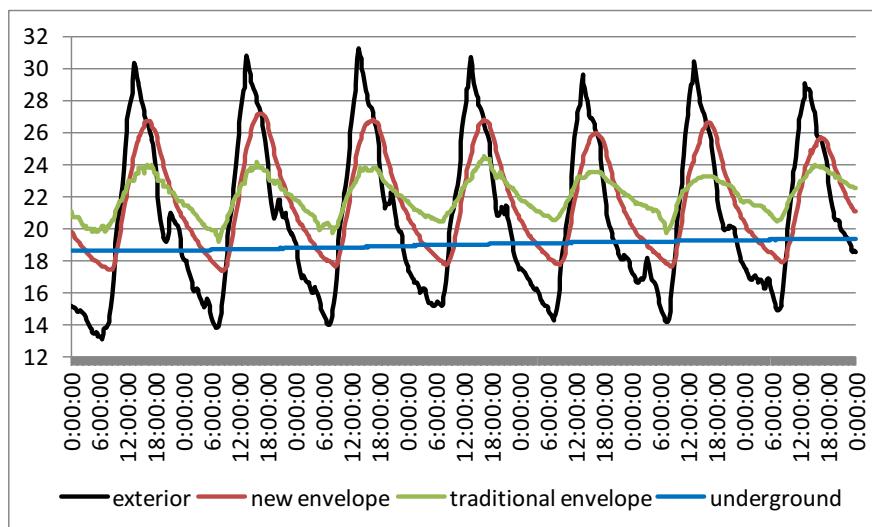


Figure 2. In situ measurements of three types of space within: a traditional envelope in winery A, a new envelope in Winery A and an underground cellar. Source: author's own.

## Discussion

Traditional old envelope keeps temperatures 8.5°C to 10°C bellow outside measurements; while temperatures in spaces within new envelopes are only 3°C to 5°C below outside temperatures.

These results are coherent with the inertia of the envelope materials. The traditional old walls' inertia coefficient was calculated between 38 and 95, while new walls have an inertia coefficient of 0.22 to 10.

Nevertheless, neither resolve completely wine production needs of climatic regulation as air temperature needs to be between 12°C to 16°C. Steel 10°C bellow the best measured temperature on-the-ground! This is the cause of the excessive energetic consumption of 8.400.000 B.T.U/hour per year in Winery A.

If the winery was underground the inertia coefficient would be around 100 for all walls and roofs. That is the main reason why it is always preferable to have the critical moments of the process, especially those that take a long time such as barrel breeding, in an underground level to save cooling energy and assure all year long stable temperatures very close to the optimal ones, as was demonstrated with the underground cellar measurements. This is a very important recommendation to take into account for new constructions.

As it is impossible to change the level of a constructed winery, and the amount of building renovation is very low, around 1%. According with Lowe, Bele, Johnston (1996), in the current speed of construction and demolition, buildings constructed before 1990 will form the majority of the total stock until the second half of the next century; the environment efforts must be towards the improvement of the existent building stock. Existents buildings are therefore objects of study as the theories expressed by Kohler y Hassler (2000).

In the case of traditional construction an adequate maintenance of the existent building and the improvement of the openings (doors, gates and windows), specially in the diminishing of air infiltration, are highly recommended. Air renovation must be efficient and flexible enough to adapt to specific ventilation needs, for example to guarantee the proper air movement during fermentation stage were CO<sub>2</sub> is produced.

In relation to new constructions in an existent winery, they must be economic and to respond to short construction times in order not to interfere with the functioning of the winery. Nevertheless, the new building must respond to the climate of the site and to the interior temperature requirements reducing to the maximum possible the energy use to condition spaces.

## References

- Esteves, A.; Ganem, C.; Fernandez, E. and Mitchell, J. (2003) Thermal Insulating Material for Low-Income Housing. *Proceedings of the 20th Conference on Passive and Low Energy Architecture. PLEA 2003.* Santiago, Chile. 9 – 12 November 2003.
- Fanzone, M.; Peña-Neira, A.; Jofré, V.; Assof, M. and Zamora, F. (2010) Phenolic Characterization of Malbec Wines from Mendoza Province (Argentina). *Agricultural Food Chemistry.* 58 (4), pp. 2388–2397.
- Guerra, J. (2003) Habitar el desierto. PhD. Universidad Politécnica de Cataluña.
- Incropera, F. P. and De Witt, D. P. (1981). *Fundamentals of Heat Transfer.* New York: John Wiley & Sons.
- IRAM 14104 (2001) *Implementación y gestión de un sistema de análisis de peligros y puntos críticos de control (Hazard Analysis and Critical Control Points- HACCP).* Buenos Aires: IRAM.
- Kohler N. y Hassler U. (2000) The building stock as a research object. *Building Research & Information* 30 (4), pp. 226-236.
- Longobardi and Hancock. (2000) Field trip strategies: s: towards understanding the passive thermal performance of buildings using the example of a case in Naples: dogana office building. In: *Proceedings of the third international conference TIA 2000: sustainable buildings for the 21st century.* Oxford, UK, 9 -12 July 2000.
- Lowe, R., Bell, M. and Johnston, D. (1996) *Directory of Energy Efficient Housing.* London: Chartered Institute of Housing Edition.
- Rivera Medina, A. M. (1987) *Entre la Cordillera y la Pampa: la Vitivinicultura en Cuyo, Argentina.* PhD. Universidad de Sevilla.



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*Design to Thrive*

## Monitoring occupant behaviour in multifamily residential buildings

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**Abstract:** Occupant behaviour is the collection of information that describes occupants' presence and interactions within the building. Such data collection has been applied to building performance simulations in order to accomplish more precise output. Diminishing the gap between predicted and real building performance requires suitable input data. The objective of this study is to present the monitoring technique employed to gather information on occupant behaviour in multifamily residential buildings in Florianópolis, Brazil. The monitoring was conducted through questionnaire applications resulting in 99 valid answers regarding occupancy, window and blinds operation and cooling system control. The data collected represents different profiles and routines for similar architectural typologies. An assessment on the monitoring technique is presented comparing it to other approaches. In conclusion, questionnaire application was considered a suitable approach to monitor occupant behaviour in residential buildings by presenting a direct and low-intrusive method for data collection.

**Keywords:** occupant behaviour, monitoring, building simulation, multifamily residential buildings.

### Introduction

Occupant behaviour models allow building performance simulation to produce predicted results closer to the real performance. According to Jia et al. (2017), implementing occupant behaviour models presents two main possibilities: to diminish the gap between predicted and actual energy use and to optimize control and operation of the active systems. However, achieving the successful implementation of occupant behaviour models into building simulation depends at first on synthesizing the information in a suitable data base. Monitoring occupant behaviour is the main approach to collect data regarding the interactions between occupants and the built environment. For this study, these interactions are defined by occupancy, window and blind operation and air-conditioning control.

Monitoring occupant behaviour may focus on one or more interactions and employ a variety of techniques. Monitoring techniques can be classified in two groups, according to their main approach. The first approach concentrate on the occupant itself, therefore, the information is collected directly from the occupant by means of questionnaires, interviews, diaries. The second approach collects the information through the deployment of equipment. Movement sensors and infrared detectors, for example, have been used to monitor occupancy (Page et al., 2008, Haldi and Robinson, 2009). Measurements of carbon dioxide concentration were used by Calì et al. (2015) to infer about occupancy in residential and non-residential buildings.

The use of equipment can be extended to monitor not only the occupant behaviour, but also the environment conditions, such as temperature, humidity, CO<sub>2</sub> concentration. The

relations between the two sets of monitored data are assessed by adaptive behaviour studies, which investigate the drives to occupant behaviour.

Andersen et al. (2013) used measurements of environmental conditions and questionnaire survey to assess the relation between indoor conditions and opening or closing windows. This adaptive behaviour study was conducted in 15 Danish residential buildings and resulted in the definition of window control patterns by applying multivariate logistic regression.

Monitoring occupant behaviour with equipment enhance the accuracy of the data collected, since it does not depend on the occupants' memory. In contrast, this monitoring approach demands higher computational and personal effort, on account of larger data sets and the need of periodical maintenance, respectively. The presence of equipment creates an impact on the occupants' privacy and for that reason may not be easily applied to residential buildings. In addition, once the occupants know they are being observed their behaviour tends to change.

For residential buildings, monitoring techniques based on questionnaire application have resulted in suitable data set by using direct questions to overcome the subjectivity associated with the occupants' answers. Its direct approach allows to expedite the data collection and reach a higher number of households.

Chen et al. (2015) applied questionnaires and detailed interview to households in Changsha, China. The data collected include information on the occupants' behaviour and their reasons, along with characterization on the building and ownership. The monitoring results were used to verify the applicability of three levels of occupant behaviour data, varying from simple to complex.

Feng et al. (2015) implemented occupant behaviour data directly into building energy simulation by using typical patterns for air-conditioning control resulted of a large-scale questionnaire survey conducted in Chengdu, China. Another approach to implement occupant behaviour data into building simulation is the development of stochastic models based on the data collected.

The necessary period varies to different monitoring techniques, from minutes to several years of measurement. In the work of Emery and Kippenhan (2006) the monitoring period was continuos during 15 years. Heating control was monitored in single family residential buildings to assess the influence of occupant behaviour and envelope thermal resistance. For studies on adaptive behaviour, the monitoring period is associated with the most demanding season. Whereas, questionnaire application can be conducted with no recurrence, reducing the monitored period. Pino and De Herde (2011) applied questionnaires with no recurrence to 91 apartments from the same residential building in Chile. The questions inquired about occupants' ventilation habits during winter and summer, and the use of heating and cooling systems. The data collected were used to develop models for window operation and natural ventilation strategies.

The objective of this work is to monitor occupant behaviour in multifamily residential buildings in Florianópolis, southern Brazil, through questionnaire application.

## Method

Monitoring occupant behaviour is the first stage in developing suitable inputs for building simulations. While varying the techniques, the data collected can be used directly in the simulations or indirectly through occupant behaviour stochastic models. In this study, we

focus on the data collection stage by presenting the technique used as well as its challenges and guidelines for future work. The method used in this study comprises the application of questionnaires to households of multifamily residential buildings and the assessment of the data collected.

Concentrating the monitoring of occupant behaviour to only multifamily residential buildings was done regarding the importance of this building typology for urban centres. Residential buildings present additional challenges in comparison to office buildings. Those challenges were explored in the guidelines, along with the description of advantages and disadvantages of different techniques able to collect occupant behaviour data.

The questionnaires were developed based on the example provided in International Energy Agency Energy in Buildings and Communities Program Annex 66. By using direct questions, the questionnaire intended to reduce the subjectivity and retrieve suitable information without misunderstandings. Since the householders could answer the questionnaire in their computer or smartphone, the questions needed to be understandable for people not familiar with this subject. The questions approach occupant behaviour on a yearly basis and focus on occupancy, window and blind operation and air-conditioning control. Only the questions referring to occupancy present distinction between workdays and weekends. Occupancy was obtained by asking the householders to fill out the period in which they are in the bedroom and living room, on an hourly basis. Since only one householder answered the questionnaires, per apartment, the questions refer to one bedroom regardless the number of bedrooms. Occupant behaviour regarding window and blind operation was collected through multiple-choice questions that presented a range of periods for opening, varying from always open to always closed. The questionnaire enquired about the presence of air-conditioning equipment in the bedroom and living room. The information about air-conditioning control was also obtained by multiple-choice questions that present a variety of frequency for its use. Identification questions provided information on the district and the floor the apartment is on.

The questionnaire was made available in digital version by means of Google Forms and shared with a group of inhabitants of Florianópolis. The valid answers obtained through the questionnaire were a result of its digital application during three months.

Initially, the questionnaire was provided in print and distributed along multifamily residential buildings in the central area of the city. This approach turned out to be ineffective due to low participation by part of the householders. In another attempt, the questionnaire was presented along with a preview of the study during householders meetings. Even after that, the in-print questionnaire received very few answers. The next approach used a digital questionnaire, which was able to reach a wider area. Google Forms allows sharing the link containing the questionnaire in a variety of platforms, assisting on its release.

The questions formulated for the occupant behaviour were tested in a small group before its release in the official questionnaire. This trial had the purpose of testing the understanding of the questions by people not familiar with the area of expertise. After this experiment, some terminologies were adapted in order to avoid queries. Also, the trial revealed that the householders were not able to identify differences in their behaviour for winter and summer seasons. Therefore, the questions were changed to a yearly basis and no longer enquiring about occupant behaviour by seasons.

## Results

Monitoring occupant behaviour through questionnaire application resulted in 99 valid answers about occupancy, window and blind operation and air-conditioning control. The valid answers were obtained for a variety of districts from Florianópolis.

According to the data collected, the use of air-conditioning is wider in bedrooms (69%) than in living rooms (38%). This has a direct relation with the amount of time spent in each room. While the bedroom has an average occupancy of 9.8 hours during workdays, the living room has an average occupancy of 5.1 hours.

Occupant behaviour regarding air-conditioning control in bedrooms focus on nighttime, as expected. The data collected showed that in bedrooms, 46% of householders use air-conditioning during nighttime only in summer and 18% of householders use it in summer and winter. As for living rooms, the most common air-conditioning control is to use it in summer, for more than one period (41%). Another behaviour regarding air-conditioning control reveals that householders turn off the system after short periods, when they feel comfortable. This behaviour was observed for 25% of living rooms and 11% of bedrooms. Only rooms with air-conditioning were taken into account for such an analysis.

The occupant behaviour regarding blinds operation presents similar tendency as for air-conditioning, i.e., the occupant interacts with blinds mostly at night. As for blind operation in bedrooms, 36% of the householders maintain the blinds closed during the nighttime. The reason for this behaviour is more associated with visual comfort and privacy than thermal comfort. For the living room, 34% of the householders keep the blinds always open. In multifamily buildings, the living room is usually attached to a balcony that provides partial shading, therefore often dismissing the use of blinds. A relation between blind and window operation appears in both rooms, as the householders answered to open the blinds when the windows are also open (19% in bedrooms and 18% in living rooms), as shown in Fig. 1

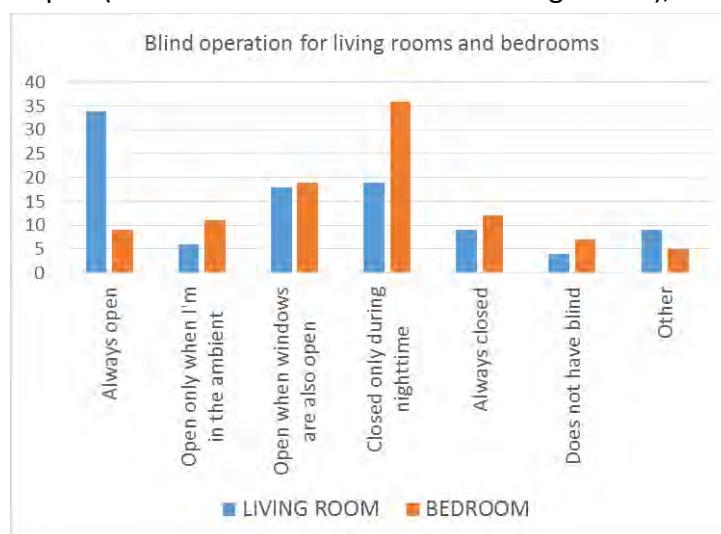


Figure 1. Blind operation for living rooms and bedrooms.

Reasons for blind operation showed a closer relation with visual comfort than to thermal comfort. As seen in Fig. 2, harness natural lighting and avoiding glare are mentioned more often than protecting from high temperatures. The desire for privacy was also pointed as a strong reason for blind operation. For this question, the householder was able to select more than one alternative and there was no distinction between rooms.

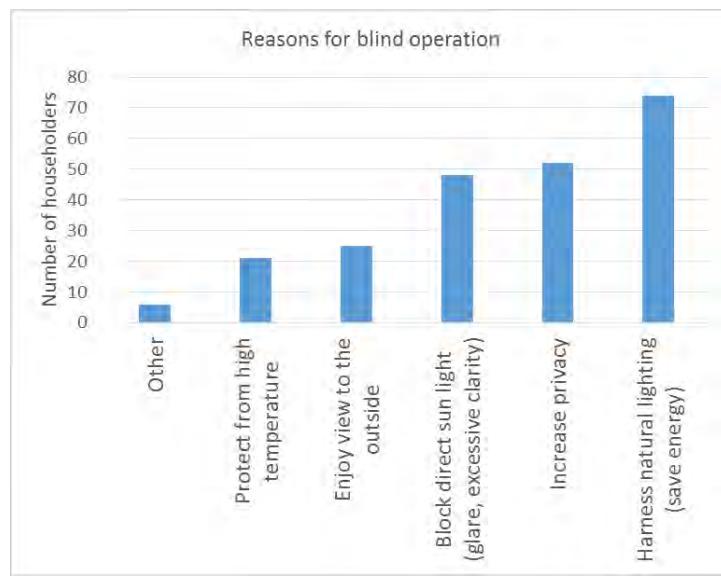


Figure 2. Reasons for blind operation.

Window operation in bedrooms highlight a specific behaviour that focus on air quality by opening the window for only short periods with the purpose of air renewal (42%). This behaviour allows to reduce indoor humidity, especially when considering the higher latent load due to an average occupancy of approximately 10 hours per day. For living rooms, the results present a variety of periods for which the window is kept open, from always open (30%) to short periods (25%), as shown in Fig. 3. The range of resulting periods may be associated with a more variable occupancy for living rooms, in comparison with bedrooms.

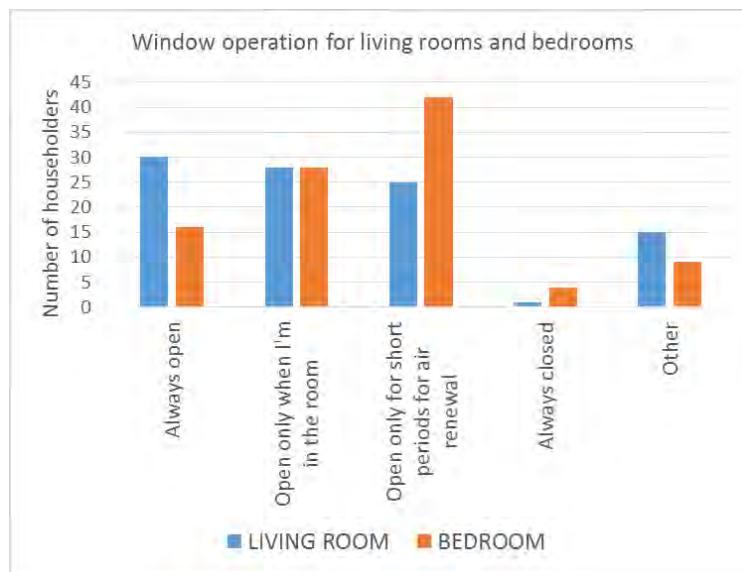


Figure 3. Window operation for living rooms and bedrooms.

For residential buildings, occupant behaviour does not necessarily follow a time routine. Therefore, human interactions are triggered by other factors other than time. It was observed that occupancy is an influence factor, especially for actions regarding window operation. Data collection for occupancy provided a characterization of occupant behaviour on an hourly basis. The occupancy results were summarised in hours. Therefore, the living room is occupied for an average of 5.1 hours a day from Monday to Friday and 7.1 hours a day on the weekends. There is a higher variation in the living room, mainly for weekends, when the standard

deviation can reach 4.5 hours. Fig. 4 shows the histogram for occupancy in living rooms and bedrooms.

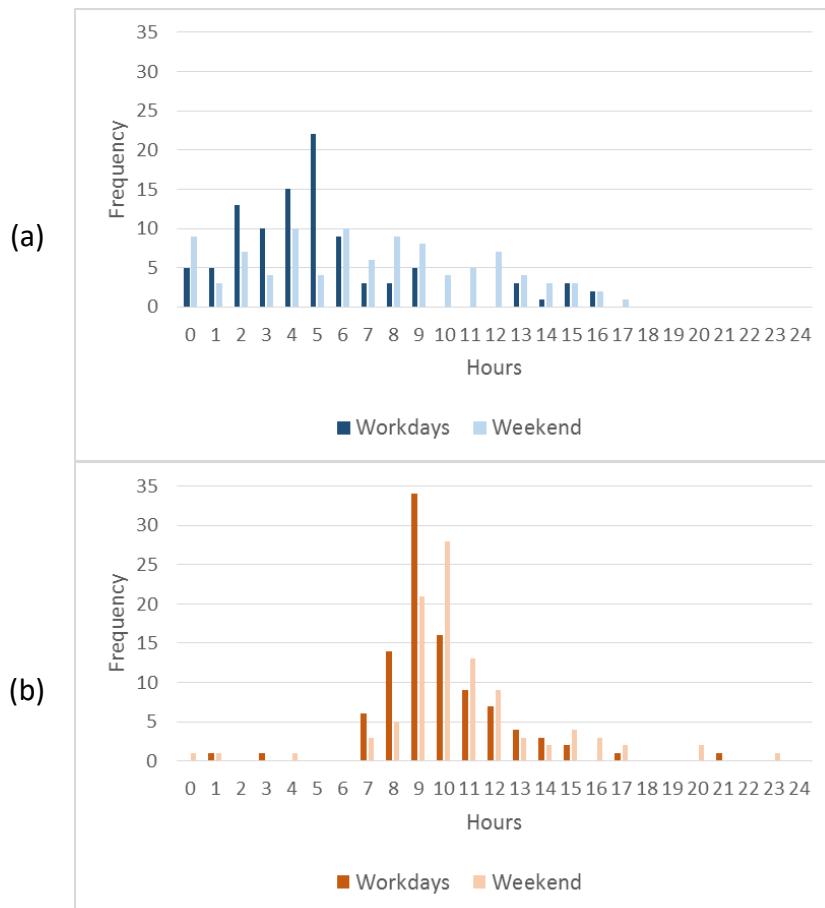


Figure 4. Occupancy for (a) living rooms and (b) bedrooms.

The histogram shows that 61% of the householders use the living room for 2 to 5 hours on the workdays. On the weekends, the use is more disperse; thus, there is a lower frequency but well distributed along the hours.

When considering the occupation of bedrooms, the difference between workdays and weekends is more subtle. On average, bedrooms are occupied for 9.8 hours a day on the workdays and 10.7 on the weekends, with a standard deviation of 3.2 hours for the latter. The histogram shows the presence of isolated points, characterizing unusual answers for occupancy. During workdays, the occupation of bedrooms concentrates in the range of eight to ten hours of occupancy per day (65%). There is an increase in the hours of occupancy over the weekend, when 39% of householders use the bedroom for more than ten hours a day.

## Conclusions

Monitoring occupant behaviour through questionnaire application has shown to be a suitable technique. The use of direct questions allows a higher comprehension by householders that are not familiar with the subject. Even though this technique presents a level of subjectivity due to the dependence of householders' memory, for example, it allows to summarise important information about the main aspects of occupant behaviour: occupancy, window and blind operation and air-conditioning control.

An emphasis was given to questions regarding occupancy, as this information was asked on an hourly basis. The importance of occupancy relates to its influence over other aspects of

occupant behaviour. As seen before, opening window only when the householder is in the room was the second most common behaviour for both bedrooms (24%) and living rooms (28%). In this paper, the monitoring results for occupancy were summarised in hours. However, the data collected by means of questionnaire application featured 99 different profiles that can be used directly in building simulation or indirectly by stochastic model.

The use of a questionnaire with no recurrence showed to be an appropriate method for residential buildings since the householders were not able to identify significant differences in their behaviour along the year. Deploying a digital version of the questionnaire allowed for reaching a greater number of respondents and overcoming the low participation found for the questionnaire in print.

The main advantage of the monitoring technique employed herein is the possibility to monitor more than one aspect of occupant behaviour at once, by a direct method that demands only a few minutes. Consequently, questionnaire application has a higher reach compared to other techniques that demand more time and resources.

The main disadvantage of questionnaire application is its subjectivity as it depends on the householder effort to retrieve suitable information. Nonetheless, part of the subjectivity can be exceeded by developing direct questions.

## References

- Andersen, R.; Fabi, V.; Toftum, J.; Cognati, S. P.; Olesen, B. W. (2013). Window opening behaviour modelled from measurements in Danish dwellings. *Building and Environment*, 69, pp. 101–113.
- Calì, D.; Matthes, P.; Huchtemann, K.; Streblow, R.; Müller, D. (2015). CO<sub>2</sub> based occupancy detection algorithm: Experimental analysis and validation for office and residential buildings. *Building and Environment*, 86, pp. 39–49.
- Chen, S.; Yang, W.; Yoshino, H.; Levine, M. D.; Newhouse, K.; Hinge, A. (2015). Definition of occupant behavior in residential buildings and its application to behavior analysis in case studies. *Energy and Buildings*, 104, pp. 1–13.
- Emery, A. F.; Kippenhan, C. J. (2006). A long term study of residential home heating consumption and the effect of occupant behavior on homes in the Pacific Northwest constructed according to improved thermal standards. *Energy*, 31(5), pp. 677–693.
- Feng, X.; Yan, D.; Wang, C.; Sun, H. (2015). A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys. *Energy and Buildings*, 117, pp. 332–340.
- Haldi, F.; Robinson, D. (2009). Interactions with window openings by office occupants. *Building and Environment*, 44(12), pp. 2378–2395.
- International Energy Agency Energy in Buildings and Communities Program Annex 66, Occupants Behavior Research Bibliography, (n.d.) <http://www.annex66.org/?q=biblio>
- Jia, M.; Srinivasan, R. S.; Raheem, A. A. (2017). From occupancy to occupant behavior: An analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency. *Renewable and Sustainable Energy Reviews*, 68, pp. 525–540.
- Page, J.; Robinson, D.; Morel, N.; Scartezzini, J.-L. (2008). A generalised stochastic model for the simulation of occupant presence. *Energy and Buildings*, 40(2), pp. 83–98.
- Pino, F. E.; De Herde, A. (2011). Definition of occupant behaviour patterns with respect to ventilation for apartments from the real estate market in Santiago de Chile. *Sustainable Cities and Society*, 1(1), pp. 38–44.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Performance analysis and practice in container building based on BIM

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**Abstract:** With the deepening of the concept of sustainable development, the industrialization of construction and the assembly building become hot spot of building industry once again. As a branch of assembly building, container building regard the container as the building parts which are designed modularized and product industrialized in factory. Also, container building has special construction method and energy-saving feature, traditional method of building performance analysis and evaluation has problems of delaying in performance analysis, difficulty in obtaining information and software cooperative abutment. Both the integrated informational platform and the parameterized family library construction function based on BIM have created new opportunities for the development of container buildings. Through the performance analysis and evaluation on a container building which is a practical project in Tianjin, China based on BIM, the paper put forward a rapid and convenient method of performance evaluation on container building which combine BIM with the architectural design performance analysis, and with a quantitative analysis of the light environment, wind environment and thermal environment which affect the performance of the container building.

**Keywords:** BIM, Container building, Building performance analysis

### Introduction

Traditional architectural design is separated from building performance analysis in the procedure of design which usually be a single line combination process (Xiaoyan,L et al,2015). Facing the problems of high energy consumption and poor comfort, the optimization of building performance from the design dimension based on BIM puts forward a new design method to reduce energy consumption and improve indoor comfort of container building.

Container building is a new construction system which has been widely focused and applied worldwide with its features of interesting variety, energy saving, environmental protection, low carbon, security and rapid construction(Lei,M et al,2014). The building uses the container as the elemental building module, and forming building with different using functions through assemble and combine one or more container which has been reformed. Meanwhile, owing to the construction system that the modular containers are produced in the factory and transported to the construction site to assemble quickly, it also meets the requirements of building sustainable, modular and industrialized development.

Based on a practical project in Tianjin, China as an example, the paper researchs on the building performance analysis for the modular design and combination process of container building based on BIM, optimizing and contrasting different design schemes, and showing the characteristics and advantages of parametric design based on BIM.

## **Green connotation of container building**

In recent years, with the rapid development of assembly building, it provides new opportunities for the development of modular container building. Most of the components of the container building are made of recycled steel, transforming and improving the container on the factory assembly line and according to the designed rules, the containers are connected by the nodes on the construction site, so that the variability of the design, the diversity of functions, the manufacture in factory and the assembly of the construction are realized. By means of the theory of modularity and assembly, the container building is designed and constructed by means of standardization, informationization and industrialization to bring the container building the green connotation of intensive, environmental protection and saving. By comparing the amount of carbon emissions during the 100 years life cycle of container building and other traditional buildings, the container building has advantages of low carbon and energy saving(Olivares,P,2010),which is an important reason for the rapid development of container building.

With the deepening of the concept of green building, the greening also put forward higher requirements to the development of container building. Although the container itself has the connotation of green, but to enable it to meet the needs of users' comfort, we also need to optimize the performance of the corresponding analysis and design (Gang,L et al,2016).Through analyzing the result of the simulation of the building performance and using the green building technology strategy to transform and upgrade the container module, the performance and quality of the container building will be improved remarkably.

## **The procedure and method of architectural performance analysis based on BIM**

Building performance simulation is a method to simulate and analyze the overall performance of the building environment and system, which mainly includes building environment simulation, building energy consumption simulation and building system simulation. And the simulation of building environment includes the simulation of light environment, the simulation of thermal environment, the simulation of wind environment, the analysis of sunshine and so on (Yiqun,P).

There are some problems in traditional methods of building performance analysis, such as the time lag of performance analysis, the difficulty of information transmission, and the imperfect connection between 3D modeling software and analysis software. In theory, the performance simulation analysis of the building should be carried out as early as possible in the early design stage, so that minimizing the probability of adverse events and reducing the waste of manpower, material resources and time because of the unnecessary rework through adjusting the design plan timely by the simulation results. By contraries, the traditional analysis of the building performance is often done after the completion of the construction design, there's no real consideration of energy-saving design requirement (Lingli, S, 2013). In the design stage, the traditional 3D models are usually not directly used by the simulation software, because it lacks the necessary information needed for building simulation and optimization, and it is inevitable to manually enter the information or rebuild a new model in the simulation software, which caused lots of repetitive modeling work, and it is inconvenient to carry out the work of performance optimization.

BIM technology is a digital expression of the project, an information sharing platform of the engineering information and it is also an engineering data model which integrates various data information related to the project based on the 3D digital technology to provide support

for all kinds of decision making in the whole life cycle of building (Kopka, W, 2015). BIM technology achieved data management throughout the life cycle of building that can produce coordinated and computable building information by means of parametric modeling, which connect all aspects of the digital model technology to make the data transfer in various stages more perfect and efficient. Therefore, different from the traditional building performance analysis, BIM technology is throughout the whole life cycle of the building, which is involved in the conceptual design stage of the building. Meanwhile, The BIM modeling software such as REVIT can input the information which required for the simulation and optimization into to model in the early stage of design, and exporting the GBXML or DXF file format which can imported into the building performance simulation software for the following simulation and analysis. The analysis process is shown below by using BIM technology to optimize the performance of the building (as shown in Figure 1).

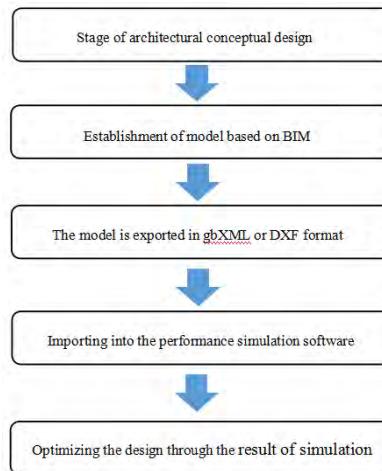


Figure 1. The analysis process of optimizing the architectural design based on BIM.

### **Application of BIM technology in container building performance optimization**

Compared with the traditional architecture, as a branch of prefabricated building, container building's particularity lies in its unified processing production in the factory, and then the modular container in different using function are combined by steel or welding method at the construction site. At the same time, its physical properties such as structure, insulation, ventilation and lighting, combination and other aspects also have particularity. So the performance analysis of container building cannot be carried out in accordance with the traditional building analysis, in the analysis process, we should fully consider the characteristics of modular, informatization, construction assembly so that truly achieving the purpose of optimization. Applying BIM technology to the performance optimization design of container building will make the traditional performance optimization process arranged reasonably, so that the optimization analysis conclusion can be effectively applied in the design of the building. According to the different functions of different modules, establishing different high performance container modules effectively through the BIM information platform and the docking way between BIM software and simulation software, and forming the industrial production procedure of modular design - factory production - assembly construction. Meanwhile, according to the characteristics of container construction, such as easy assembling, disassembling and easy to move, in the design stage, optimizing the design of the internal space of the container building, through using the REVIT library functions, to

form variable furniture library suitable for different scenarios which can facilitating building's management in use process (As shown in Figure 2).

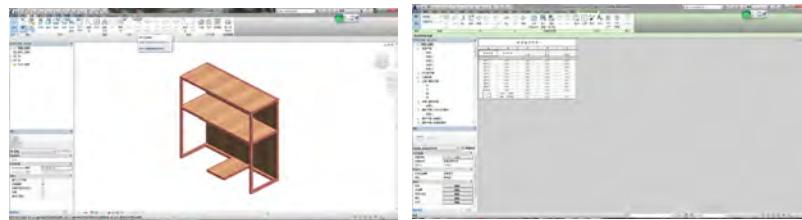


Figure 2.The family library and selection manual of furniture in container building.

The 668 document of the international organization for Standardization (ISO) has established the global standard of container, which provides the standard and the basic module requirements for the development of container building (ISO, 2013). Based on the concept of assembly, the industrialized production method puts forward new requirements for the standardized design of the container. Using the BIM library function, the container unit is standardized to form a standard unified container library. On the basis of standardization, the container units with different forms and functions are rich, the integrated production of the factory and the overall efficiency are improved. A single container module usually consists of main frame structure, roof, wall and connecting nodes (As shown in Figure 3), and each module is designed and product by different way according to the different functions. The project has carried on the research of the modular library and the variable space design for office for single, office for four people, living for single, living for four people and several modules (As shown in Figure 4).

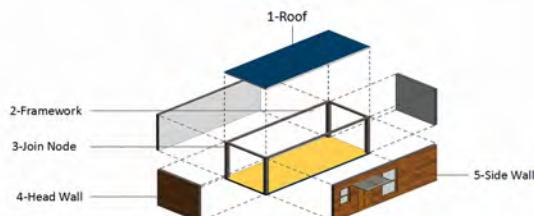


Figure 3. Exploded drawing of the container module.

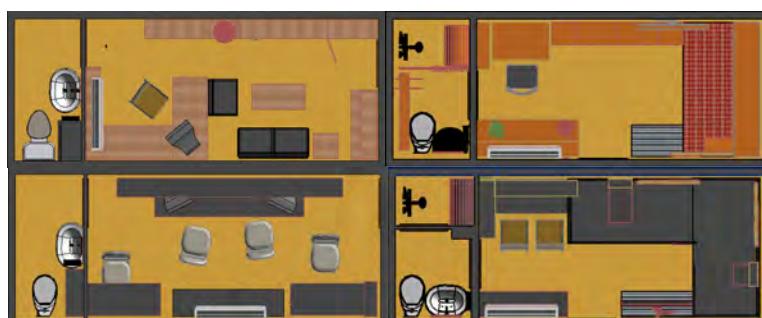


Figure 4. Building information model of different container modules.

### ***The establishment of building information model***

The three-dimensional information model based on REVIT is the basic concept of BIM, and transmitting the building information through the model with the characteristics of informatization and parameterization, including the collection information, material properties, componential attributes and so on. So we can only get the simulation results by importing the model with information into the simulation software. For this project, the

author established the BIM model with the required information in the early stage of design (As shown in Figure 5).

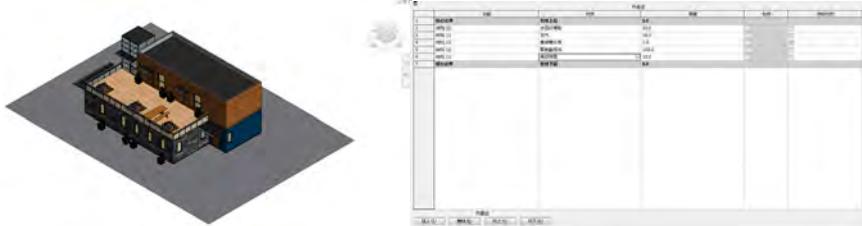


Figure 5. Building information model of the project and the information of its wall.

### ***Site planning and building orientation analysis***

#### ***Project overview***

The project is located in Tianjin, China, where has continental climate, four distinct seasons, the city's monsoon prevails, and the wind speed in winter and spring is the largest, which is minimum in summer and autumn. The annual average wind speed is 2m/s to 4 m/s, mostly is southwest wind. The annual average temperature is about 12°C and the quantity of annual average rainfall is about 600mm. Meanwhile, the design function of the building features to office-based, both living function.

#### ***Analysis of climatic condition and building orientation***

In the preliminary design stage, climatic conditions in the project is analyzed by using BIM technology. Comparing the amount of solar radiation and orientations, the optimum orientation can be obtained: South east 17 degrees; Formulating the strategy for the most comfortable passive energy conservation through analyzing psychrometric chart and the relevant passive strategies (as shown in Figure 6); Identifying the spacing between the containers and their arrangements through analyzing the architectural composition and shadow range (as shown in Figure 7).

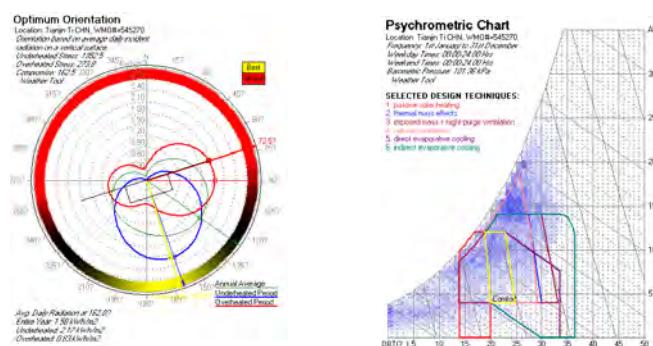


Figure 6. Solar radiation, best toward and psychrometric chart.

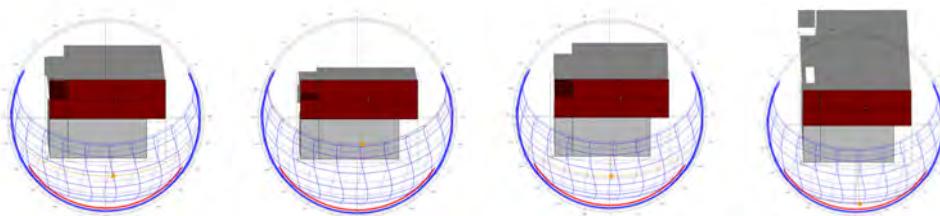


Figure 7. Analysis of shadow range.

#### ***The performance optimization design of light environment***

The performance optimization of light environment mainly concerns the reasonable design for the openings of the container building. Through the REVIT model importing into the

simulation software ECOTECT and simulating the effect of the natural lighting, the simulation results of natural illumination coefficient of the building and the indoor natural lighting illuminance in winter solstice can be obtained (as shown in Figure 8).

By comparing with the standard, the reception area's illumination and lighting coefficient of the building is low. Because of the dim light, the area of opening the window towards the south side of the wall and the end wall of the east side should be expanded. Meanwhile, the illumination and lighting coefficient of the meeting room on the east side is high, so sun shading measures should be adopted. According to change the parameterized data such as the openings' size and the different shading forms based on BIM, the design can be optimized and upgraded easily, and it can be convenient to confirm the new form of openings which meets the lighting requirements of building (as shown in Figure 9).

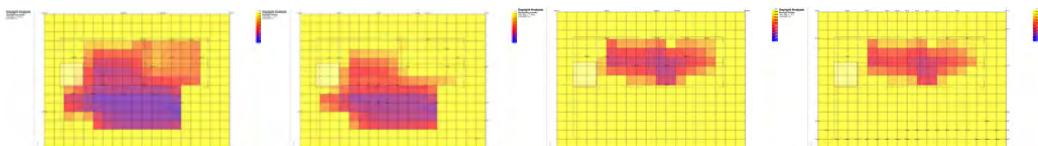


Figure 8.The simulation result of natural lighting and illumination coefficient of the building.

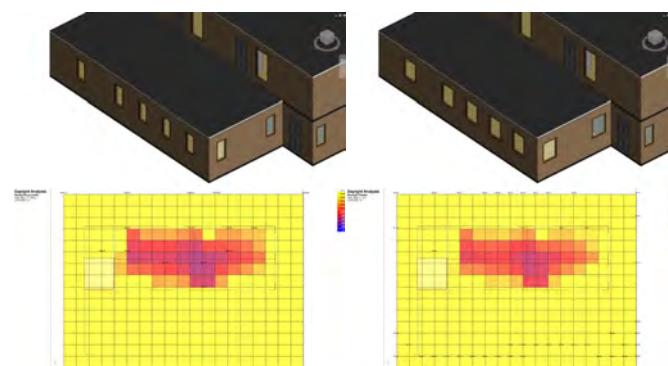


Figure 9.Comparison before and after optimization of the building and the simulation result after optimization.

#### *The performance optimization design of wind environment*

The design of natural ventilation based on the site and climatic environment is an important link for reducing the energy consumption of the architecture and optimizing its design. At first, the natural ventilation is designed according to the architect's concept, building openings with certain numbers and sizes in all around of the building to establish an early BIM model. After that, importing this entity model into the analysis software of wind simulation PHOENIX to simulate natural ventilation indoor and outdoor, and setting certain parameters in PHOENIX according to the specifications, which can conduct some simulations to get the nephogram of indoor wind speed, the vector diagram of wind velocity in this container building and some other results. It can be seen from the exported figure that the indoor wind speed in the building keeps  $0.5 \text{ m/s} \sim 1.5 \text{ m/s}$  (as shown in Figure 10), which can meet the requirements of people's working and living comfort in the building. The result validated the initial design of natural ventilation, optimized the design procedure of the building, and also provided scientific basis for design.

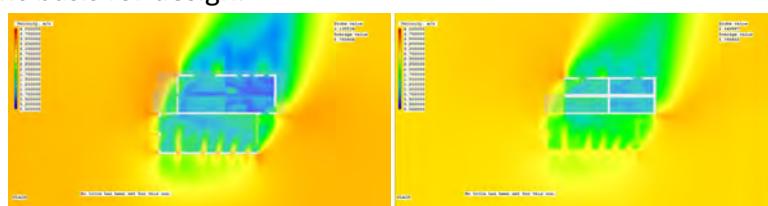


Figure 10.Velocity nephogram of indoor ventilation of the building.

### *The performance optimization design of thermal environment*

According to statistics, the energy consumption of buildings in the process of constructing and operating accounts for nearly 50% in the overall global energy (Bo, L, 2014). As parts in modular production, container building has great significance on the design of the wall heat preservation, structural insulation and other properties in the early design stage. Compared with traditional methods, the application of BIM technology can make the data input more efficient in evaluating and analyzing the energy consumption of the building. We can obtain the feedback of information of energy consumption timely. On the basis of these feedback, we can continuously compare the updated simulation results in order to improve the efficiency of the green design. REVIT, has good qualities of compatibility and information transmission with the energy consumption simulation software DESIGNBUILDER. In this project, we imported the REVIT model into DESIGNBUILDER through the way of additional module (as shown in Figure 11), and modified the information appropriately in DESIGNBUILDER, which can assist us in acquiring related information of the building, such as its cooling load, heat load, energy consumption and so on. Among the result, the exterior-protected construction load and the external ventilation account for a higher proportion of the sensible heat load. In the exterior-protected construction, the glazing and the wall are the two parts of the maximum heat load, which respectively account for 26% and 14% of the sensible heat load. The time of outdoor temperature peak is about 14:00, and because of the influence of the delay of exterior-protected construction, the peak value of cooling load of the building is delayed to about 17:00, the maximum value of building cooling load appears in August, and the peak of heat load appears in February. Based on these analysis data, it provided us the design basis for the design of HVAC system and the establishment of the overall operation control strategy (as shown in Figure 12).

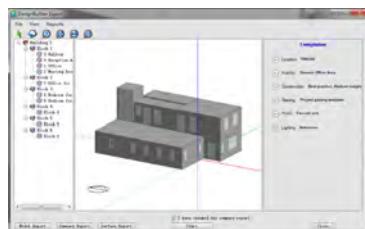


Figure 11.The page connecting REVIT and DESIGNBUILDER.

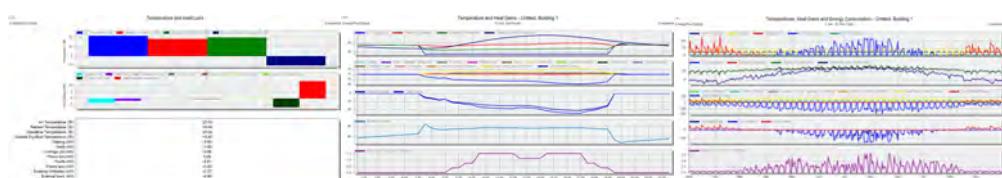


Figure 12.The simulation result of load and energy consumption of the building.

### *Safe evacuation optimization design*

Recent years, the number of large volume and high-level container building is increasing with the extensive development of container building, so it is of great practical significance to study the evacuation of personnel in container building. In this project, based on the characteristic of information integrity and compatibility with simulation software of BIM technology, the study of personnel evacuation was carried out by introducing the BIM model established by REVIT into the simulation software PATHFINDER(Guerrero-Bote, V et al,2006), providing effective information for building safety management (As shown in Figure 14). It is concluded by simulation that the emergency evacuation time is 26.5 seconds when there are

30 people working or resting in different rooms in the building, which providing feedback and guidance for the fire protection design of the building (As shown in Figure 15).

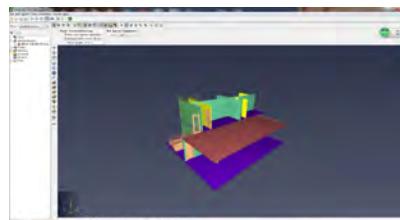


Figure 14. REVIT imports into PATHFINDER.

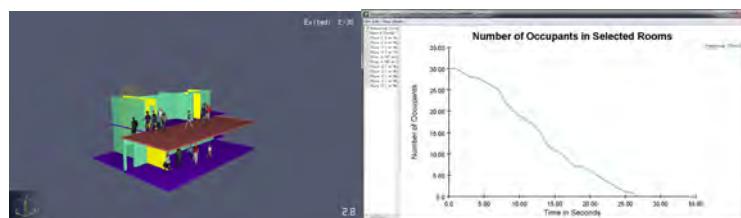


Figure 15.The result and chart of evacuation simulation.

## Conclusions

The paper clarified the model that apply the BIM technology in the design of container building through introducing the relationship between the performance optimization of container building design and BIM technology. Based on the analysis of the existing problem in the traditional building performance optimization, a method of building performance analysis based on BIM is proposed. Taking the practical project in Tianjin, China as an example, the paper analyses the performance of container building based on BIM from different perspectives of the site planning, building orientation analysis, architectural environment of natural lighting, natural ventilation and thermal, and the safe evacuation, and verified its feasibility effectively. Meanwhile, it is also provided a new green design idea for BIM technology to apply to container building and even to assembly building.

## References

- Xiaoyan,L.,Kai,W.(2015).Practice of BIM Integrated Building Performance Analysis-Aspect of Green Energy Saving.Journal of Information Technology in Civil Engineering and Architecture,(01),pp.14-19.
- Lei,M.,Ye,L.,Guoqiang,L.(2014).Overview of the History and Applications of Container Buildings.Progress in Steel Building Structures,(05),pp.9-17+43.
- Olivares, P. (2010).Sustainability in Prefabricated Architecture: A Comparative Life Cycle Container Architecture for Residential Structures. Victoria University of Wellington.
- Gang,L.,Ye,Y.,Dan,H.,Rui,D.(2016).Research and Practice:The Performance Optimization Design For Container Buildings.Eco-city and Green Building,(03),pp.59-64.
- Yiqun,P.Practical Building Energy Simulation Handbook.China:China Architecture & Building Press.
- Lingli,S.(2013) Comparative Research on Building Energy Consumption Analysis Based on BIM with Traditional Building Energy Consumption Analysis of China.Master.Chongqing University.
- Kopka, W. (2015). Open BIM - IFC. Mechanik, (7), pp.562/425-562/434.
- International Standard Series 1 freight containers-Classification,dimensions and ratings. International Organization for Standardization. (ISO/TC 104/SC 1). 2013
- Bo,L.(2014)Research on the Analysis of Energy Consumption at the Beginning of the Architectural Design Based on the BIM Technology.Master.Chongqing University.
- Guerrero-Bote,V.,Zapico-Alonso,F.,Espinosa-Calvo,M.,Gómez-Crisóstomo,R.and Moya-Anegón,F. (2006). Binary Pathfinder: An improvement to the Pathfinder algorithm. Information Processing & Management, 42(6), pp.1484-1490.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Reducing Agitation in Dementia Patients: A role for environmental design

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**Abstract:** The need to increase the purpose built dementia care homes raises the profile of environmental building design considerations and how they relate to reducing agitation in dementia patients. Critical to the increasing population with dementia, is a need to change the social perceptions of mental health facilities as linked to the design of asylums and prison architecture. The availability of facilities that educate, rehabilitate and provides therapeutic and healing environments is a need for both patients and their carers. Literature suggests that well designed environments for a small group of patients in a home like environment influences dementia patients' behavioural attitude and aid in retention of physical abilities to move within the spaces and reduces agitation levels. (Lawton,2001, and Nagari, 2016). This is a preliminary review of research published between 2010- 2017 linking the impact of building design decisions to environmental effects on dementia patient behaviours in care homes. It is argued that in the pursuit for decreasing energy consumption by design and building fabric specifications of these homes, more research and a deeper understanding of environmental health related guidelines need to be considered before the building is built. A central role for building performance evaluation and modelling needs to be included in the design approval process that necessitates further research on ranges of daylight, lighting, thermal comfort and acoustic levels to be achieved. This research reviews literature relating the quality of life of dementia patients to the quality of the designed space and the environment it creates.

**Keywords:** Dementia, building environment, agitation

### Introduction

The World Health Organization defines 'dementia' as a syndrome leading to a set of symptoms that lead to deterioration in memory, difficulties with thinking and problem-solving, verbal communication and the ability to perform daily tasks. These changes are often incremental at the beginning till they reach a stage where patients need to be hospitalized or taken into care homes. A person with dementia may also experience changes in their mood or behaviour leading to agitation and pain (Cohen-Mansfield et al (2015). the Alzeheimers society (2015) estimates that there were about 850,000 people in the UK with dementia with an estimated growth to 2 million by 2051. It mainly affects people over the age of 65, where one in 14 people in this age group have dementia. The proportion of people doubles for every five years gap and one in six people over the age of 80 will be diagnosed with the disease. There are more than 42,000 people in the UK under 65 with dementia. It is estimated that the cost of care for dementia patients costs the country £26.2 billion annually (enough to pay for energy bills for every household in the country).

Dementia is diagnosed when the brain cells are damaged. Alzheimer's disease is the most commonly diagnosed form, but other forms such as Vascular dementia following a

series of strokes leading to reduction of oxygen supply to the brain. Dementia with Lewy bodies also linked to Parkinson disease and leads to difficulty with movement. Frontotemporal dementia (including Pick's disease). Mixed dementia where a patient can be diagnosed with different types of dementia. The specific symptoms that someone with dementia experiences will depend on the parts of the brain that are damaged and the disease that is causing the dementia.

### **Understanding the disease; informing the building production:**

The complexity of designing buildings that reduce agitation in dementia patients stems from the fact that these buildings are a mixture of investment opportunities for developers, workplace for carers, a home for the patients and a place where families trust that their loved ones are comfortable and catered for.

The overall complexity of designing buildings for a specific patients with Dementia (PWD) as a user group with highly specialized care needs; requires an interdisciplinary dialogue between various building specialists. This is complicated by the need of specialists to capture all these building design demands in a single building production that encompasses the often contradicting stakeholders demand on the building design, construction and in use processes. For example; a cost effective design that facilitates collective care in wards but also allows for isolation, or/ and issues of cost of care and allowing comfortable indoor environments compared to the cost of continuous provision of energy in these buildings. In this paper there is a focus on the relationship between the specific nature of this disease and factors that directly affect the design of its environments for patients. van Hoof et al (2013) identifies 15 aspects that should be taken into consideration when designing for PWDs. The HBN 0802, Dementia friendly health and social care environments (2015) states twelve principles that need to be taken into consideration when designing buildings. These principles include many aspects relating to how patients might feel in the building, how buildings can express certain values or religious beliefs. Other essential parts of these models inform the programmatic resolution of design elements in plan and their relationships to facilitate way finding, justice in providing privacy, and maximum and sustained autonomy for users with lesser cognitive abilities. Building performance evaluation offers a unique opportunity to test the performance of buildings for specific user groups before the building is built. The Factors that are of pertinence to this research and the role environmental design and its assessment through building performance simulation can be deducted as:

Neurodegenerative factors that maybe reduced through building design are:

day-to-day memory – for example, difficulty recalling events that happened recently, leading to the need to create a homelike environment

concentrating, planning or organising – for example, difficulties making decisions, solving problems or carrying out a sequence of tasks, such as finding a toilet and washing up

Disability in communicating verbally to convey unmet needs expressed though agitated behaviours or what maybe interpreted as inappropriate sexual behaviour such as feeling thermally uncomfortable, over stimulated by glare or noise levels in the space leading to taking off clothes in public (van Hoof et al 2010)

visuospatial skills – for example, problems judging distances (such as on stairs) and seeing objects in three dimensions, shadows from lighting fixtures being perceived as holes on the ground, or two variations between two flooring materials being perceived as a step.

orientation – becoming confused about where they are and time of the day relating to wandering behaviours and sundown syndrome, needing clearer landmarks and cues for triggering memory of how to use the space.

Table 1: factors for holistic design considerations in Dementia Friendly care homes and facilities

HBN 0802	van Hoof et al (2013)
Principle 1 provide a safe environment	Numerical how patients understand numbers and symbols in various spaces
P2 optimum levels of stimulation	Spatial referring: to how patients can navigate the buildings and understand its various parts
P3 Optimum level of lighting and contrast	Physical: referring to indoor environmental conditions of heat and ventilation
Cognitive impairment principles	Logical analytical referring to differences between PWDs and healthy individuals in their ability to analyse their environments and how to move in between
P4 provide a non institutional scale and environment	
P5 support orientation	
P6 Support way finding	Formative: how patients can autonomously control their daily lives
P7 provide access to nature and outdoors	Biotic how patients have access to sensory experiences in the building and outside
P8 Promote engagement with friends	Social: referring to facilitating interaction between patients, other patients, carers and family
P9 promote good visibility and visual access	Sensitive: how patients can see and perceive reality of their various environments compared to a health adult
P10 Promote privacy and dignity	Juridical supporting privacy and varying needs for isolation at times
P11 promote meaningful physical activity	Creedal supporting religious symbolism and activities among other activities
P12 support hydration	
	Informatory: referring to their lingual ability to communicate meanings of symbols, emotions and words
	Ethical : how the whole building design should facilitate care and support a healing environment, using technologies to detect patients behaviours such as agitation or wandering
	Esthetical referring to how the building interior and exterior architecture is appreciated by PWD
	Economic: how can health care costs be minimized without compromise to quality

HBN 0802, Dementia friendly health and social care environments (2015) states twelve principles that need to be taken into consideration when designing buildings, the ones that are most related to environmental design and can indeed be tested through building

performance simulation are P3 and P9, while P2 (optimum level of stimulation) is also linked to reducing thermal and acoustic stressors and should be tested by building performance simulation at design phase. Van Hoof et al (2013) model refers to these environmental stressors highlighting their impact on cognitive abilities and their role in cognitive deterioration if not considered earlier in the design stage.

The impact of the building design on particular dementia patients behaviours is assessed by a number of measures that are used in research and medical trials to test the impact of the environment on dementia patients, it is noted that these measures are used by proxy as care givers are asked to use the ratings to respond to factors affecting patients with dementia. Such as Alzheimer's Disease related quality of life ADRQL scale that contains 40 items divided into social interaction, awareness of self, feelings and mood, enjoyment of activities and response to surroundings. The Neuropsychatirc Inventory (NPI) used to quantify the severity and frequency of 12 neuropsychiatric symptoms related to dementia, namely delusions, hallucinations, agitation and aggression, dysphoria, anxiety, dysphoria, euphoria, apathy, disinhibition, aberrant motor behaviour, sleep and appetite disorders. And the Hopkins Homelike environmental Rating Scale

van Hoof (2010) report 36 behavioural disorders based on a literature review in Dementia patients. Five of these behavioural disorders were identified as directly related to building design as identified by literature reviews of more than 250 research outputs collectively found till 2010 namely: Disorientation, impaired sense of time, impaired wayfinding, agitation, sundowning and aggression. Nagari and Hamza (2016) also reported a potential link between daylight availability linked to the façade design and orientation and an increase in aggression incidents in a care home that was monitored in 2015.

## **Methodology**

A set of criteria was designed for inclusion of research

1-The literature survey looked into relevant research undertaken since 2010- 2017 using various data basis namely sciencedirect, Pubmed and googlescholar. The keywords used were Dementia combined with care homes, energy consumption, behaviour and environment.

2. Evaluated an intervention utilising the physical environment with an impact on dementia patients' behaviour

3. Incorporated a control group, cross sectional or survey design of case study buildings specifically designed for dementia care or incorporated specialized wards in elderly care homes.

4. Research relating to interior design and fittings was excluded such as studies relating to positioning of furnishings, home likeness, paintings and plants.

As the positive relationship between these design elements and reduced agitation and wandering in patients was extensively reviewed by Fleming et al(2009) A review of the empirical literature on the design of physical environments for people with dementia found a direct link between Environmental determinants of quality of life in nursing home residents with severe dementia.

## **Healing or agitating environments?**

Finding the relationship between our current state of knowledge of environmental influences and relationships whether directly or indirectly between architectural design of these care facilities and the agitation levels of dementia patients highlighted the need for a framework for design and design quality analysis. Brahman et al (2014) draws attention to the importance of relating the senses in the diagnosis and management of dementia Associations between dementia and impairments in hearing, vision, olfaction and (to a lesser degree) taste have been identified.

Hearing impairment has been shown to precede cognitive decline, but it is not clear if the hearing loss is an early marker of dementia or a modifiable risk factor.

Olfactory impairment is seen in many neurodegenerative conditions, but it has been shown that those with dementia have particular difficulties with the recognition and identification of odours rather than the detection, suggesting a link to impairment of higher cognitive function. Olfactory impairment has been shown to be predictive of conversion from mild cognitive impairment to Alzheimer's disease with 85.2% sensitivity. As cognitive function deteriorates, the world is experienced at a sensory level, with reduced ability to integrate the sensory experiences to understand the context. Thus, people with dementia are very sensitive to sensory experiences and their environment needs to be managed carefully to make it understandable, comfortable, and (if possible) therapeutic. Light can be used to stabilise the circadian rhythm, which may be disturbed in dementia.

Identifying sources and indications of discomfort maybe directly related to factors such as quality and quantity of nursing, or the medical state of the patients. Cohen-Mansfield et al (2015) defining discomfort and pain in Dementia patients as related to medical and non-medical factors using the Sources of Discomfort scale (SODS). It is the environmental sources of this scale that links with frameworks in Table 1.

- (1) *Physical* (i) *Hunger/thirst*: the desire to consume food without prompting
- (ii) *Rash/fungus*: seeming to try to scratch a body part, excessive touching of clothing.
- (iii) *Constipation*: examined from medical records
- (iv) *Sleepiness or tiredness*: seeming to be excessively sleepy or tired
- (v) *Feeling uncomfortable*: noted from subjective responses of patients about how they feel
- (vi) *Bathroom*: resident asking to go to the bathroom.

### *(2) Body positioning and movement*

- (i) *Seating*: observations of how patients were moving in the seat, head lying unsupported, leg dangling, leg stuck in the wheelchair or another piece of furniture, other body parts looking uncomfortable using the reasonable person test, and sitting in the same place without movement for over two hours .

### *(ii) Restraints*: resident restrained

- (iii) *Furniture positioning*: furniture standing in the way of the resident. Providing a non institutional feel and provide a friendly environment for engagement with carers family and friends. Support orientation between spaces.

### *3) Environmental sources*

Of particular importance to the role of the architect and building performance modelling is the environmental sources of discomfort and how they can be mitigated by user centric design. The opportunities to simulate the environmental performance of these care facilities by using specialized building performance modelling should not be missed.

- (i) User centric approaches to building programme and functional positioning of rooms and linking corridor spaces to help promote privacy, dignity and independence as long as possible.
- (ii) Wayfinding with colour contrasts as cues and avoiding bland unstimulating environments

*Providing optimum levels of Lighting:* is there a link between insufficient lighting and agitation?, and its evidence to ‘sun-downing’ syndrome, or evidence of over stimulation due to higher levels of lighting. Is the creation of shadows from daylight design or artificial lighting a problem? Providing good visibility but without over stimulation

- (ii) *Thermal comfort:* complaints of being hot or cold

(iv) Acoustical comfort: noise levels and quietness: another resident is bothering the resident

(v) olfactory comfort; presence of adequate natural ventilation, odours from sensory gardens

Cleanliness management systems would contribute to this perception but were excluded from the analysis.

- (Vi) ease and secure access to the outside spaces and natural environments

Research highlighted that environmental stressors are also exacerbated by the level of control the patients and their carers may have on the environment of the care home. Walker et al (2016) argue that in the six care home environment they monitored, this degree of agency and control is curtailed to some degree and bounded for individual residents. Instead, agency and control are distributed to the different ‘non-resident actors’ within the home, as PWD may not be able to control the settings and end up merely playing with the thermostat. across the range of staff there could be deliberate delimitations of responsibility that introduce both technical and human ‘intermediaries’ between the subjects of comfort and the setting of ambient temperatures in the rooms they were occupying. Care staff sometimes felt unable to make adjustments to the heating systems, even where they were formally able to, because of their lack of understanding of how the heating system worked and lack of confidence in their ability to exercise control over it correctly – particularly where an unfamiliar technology such as underfloor heating was involved. Mendes et al (2013) attributed the increase in Fungal concentrations frequently exceeding reference levels (>500 colony-forming units [CFU]/m<sup>3</sup>) to the quality of the building fabric but also to the lack of individual control over the environment.

Van Hoof et al (2010) warn that Some sensory technology that may be useful in theory, such as lights that turn on by motion sensor to guide people to the bathroom at night, may be confusing and distressing to some people with dementia. Therefore, a careful balance must be struck to use technology appropriately to maintain a comfortable and understandable environment and to keep patients safe without negatively affecting their quality of life.

Van Hoof et al (2010) based on an extensive literature review of It is hypothesised that high-intensity lighting, with illuminance levels of well over 1,000 lx, may play a role in the management of dementia. Bright light treatment with the use of light boxes is applied to entrain the biological clock, to modify behavioural symptoms, and improve cognitive functions, by exposing people with dementia to high levels of light. The results of bright light therapy on managing sleep, behavioural, mood, and cognitive disturbances show preliminary positive signs, but there is a lack of adequate evidence obtained via randomised controlled trials to allow for a widespread implementation in the field. Van Hoof (2010) reviewed more

than 140 key research journals and guidelines in an attempt to identify the key factors that relate between the senses and building design factors in houses for Dementia patients and care homes. Concluding that understanding of lighting is well established and should be between 300-1000 Lux depending on function of the space, this was also supported by the Building Health notes in the UK. (2015). However, post occupancy evaluation of case study care home in Galicia in Spain (Rodriguez and Hamza (2016) and one detailed study in the UK (Nagari and Hamza, 2016) found that daylight levels were not really achieved in care homes and were below the levels anticipated.

Linking building design and agitation behaviours in Patients with Dementia highlights the missed opportunities of not mandating the use of Dynamic building performance simulation modelling and the urgent need to understand indices of building performance based on a specific and scientific knowledge of thermal and visual comfort indices for PWD

## Conclusions

Performance modelling to reduce energy demand in supporting the design of mental health facilities with special emphasis on dementia care. Age UK and various NHS publications acknowledge the impact of the built environment as a healing accelerator. The bulk of research acknowledges the impact of sensory, cognitive and physical impairment that healthcare buildings can create if not designed fit for their purpose. Although BREEAM H for sustainable buildings and the use of complex softwares for Building Information Modelling (BIM) is mandatory for all large public centrally procured projects to optimize the construction processes, the 'Building and Urban Environmental Performance Simulations' have not been included in the early design assessments. The current attempts by the NHS to collect patients' feedback related to cleanliness and safety of facilities (PLACE), can give some guidance to building design but not enough for creating critically needed sensory and performative buildings for healthcare.

The reviewed research found that, albeit, the advances in understanding the link between a faster cognitive deterioration due to the built care home environments, the critical question of how can we integrate a better understanding of generic design guidelines (Health Building Notes HBN 08-02, 2015) for dementia and social care environments into applicable and measurable design parameters for architects and urban planners for existing and new buildings still remains unanswered.

## References

- HBN 0802, Dementia friendly health and social care environments (2015)
- van Hoof J., Verkerk M. (2013) developing an integrated design model incorporating technology philosophy for the design of healthcare environments: A case analysis of facilities for the psychogeriatric and psychiatric care in The Netherlands, Technology in Society Vol. 35, pp. 1–13
- Negari K, and Hamza N. (2016) Assessment of Daylight in Relation to The Agitation Levels of People with Dementia, in Hamza, N and Underwood C.(Ed) Third IBPSA-England Conference Building Simulation and Optimization, Newcastle University, Newcastle- Sept 12-14<sup>th</sup>.
- Rodriguez M, and Hamza N.(2016) Assessment of Indoor Visual Environments Using Dementia Friendly Design Criteria in Day Care Centres, in Hamza, N and Underwood C.(Ed) Third IBPSA-England Conference Building Simulation and Optimization, Newcastle University, Newcastle- Sept 12-14<sup>th</sup>.
- Fleming R., Crookes P. and Shima Sum (2008) A review of the empirical literature on the design of physical environments for people with dementia, a report, available on <http://ro.uow.edu.au/cgi/viewcontent.cgi?article=3923&context=hbspapers>

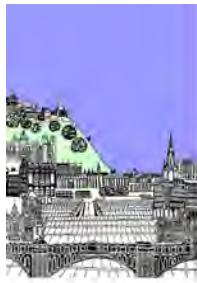
Cohen-Mansfield J., Marcia K., Marx S., Dakheel-Ali M. and Barbara Jensen (2015) Sources of Discomfort in Persons with Dementia: Scale and Initial Results Behavioural Neurology, Volume 2015 Article ID 732832, 6 Pages <http://dx.doi.org/10.1155/2015/732832>

Lawton M. (2001) The physical environment of the person with Alzheimer's disease, Aging and mental health pp. S56-S64)

World Health Organization, Dementia, key facts, <http://www.who.int/mediacentre/fs362/en>

Gordon Walker G., Brown S. & Neven L.(2016) Thermal comfort in care homes: vulnerability, responsibility and 'thermal care', Building Research & Information, 44:2, pp.135-146

Mendes A. Periera C. Mendes D, Aguiar L., Neves P., Silva S., Batterman S., and Teixeira J. (2013) Indoor Air Quality and Thermal Comfort—Results of a Pilot Study in Elderly Care Centers in Portugal, Journal of Toxicology and Environmental Health Part A 76(4-5):333-44



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Towards a Holistic approach to Low Energy-Building Design: Introducing Metrics for Evaluation of Spatial Quality

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**Abstract:** Building renovation is a complex task involving many stakeholders with different agendas. Therefore, various methodologies for assessing the impact of renovation initiatives on stakeholder agendas have been proposed. However, recent research questions contemporary practice in this matter and points out that the developed methodologies tend to favor technical (quantitative) values over more qualitative values, such as the potential to improve the perceived spatial quality in a manner that builds on the existing qualities and reflects contemporary social and cultural values. This paper discusses how to introduce metrics for more qualitative value creation in renovation processes. The hypothesis is that metrics for e.g. spatial quality can be established and used for decision-support in the early phases of renovation projects. The paper focuses on how to translate qualitative values related to human comfort and spatial perception into metrics, which can be operationalised for design information and performance evaluation. Examples of metrics related to façade properties are put forward and form the basis for a discussion about the relevance of including and quantifying such metrics as an integral part of a holistic approach to low energy-building design.

**Keywords:** Building Performance Evaluation, Architectural transformation, Refurbishment, Energy renovation, Spatial Quality

### Introduction

The building sector accounts for up to 40 % of the total energy consumption in the EU. Considering that the vast majority of the existing building mass will still in operation in 2050, it is evident that there is a significant energy saving potential in renovations rather than focusing solely on building energy efficient new buildings (Government, 2014b). A significant proportion of this potential lies in existing private households, which accounted for approx. 25% of the total energy consumption in the EU in 2011 (European Commission, 2016). In Denmark, there are approx. 566.000 social housing units, which constitute 20 % of different types of ownerships (Statistics Denmark, 2016). The vast majority of these were built before the energy saving requirements in the national building regulations were tightened in the late 1970's. As such, there is a significant potential for reducing the overall energy consumption in the building sector by addressing this particular building typology (Government, 2014a, p. 56). The dwellings of the future already exist, so to speak, and we have been entrusted the task of updating them in a way, which complies with todays' energy standards while at the same time respecting their cultural and social significance.

This is, however, easier said than done. Renovation projects commonly involve a number of stakeholders, with each their own perspective. As such, they make up highly complex, or “messy”, systems (Churchman, 1967). As a response, later years have seen the development of different methodologies for evaluating the performance of the building prior to renovation and after completion. In this study, we focus on performance evaluation in the pre-renovation phase. To be more precise, we focus our attention on the concept development phase in which design freedom is still relatively high, but the knowledge about the project in its entirety is limited (figure 1). Despite this paradox, we are often obliged to make design decisions, which have high consequences for the overall outcome of the renovation. As such, building performance evaluation could be a tool for decision support at a crucial stage in the process and a way to make sense of the complex system it composes. By this, we do not intend to replace the creative process, but to provide inputs, which can inform the decision-making processes.

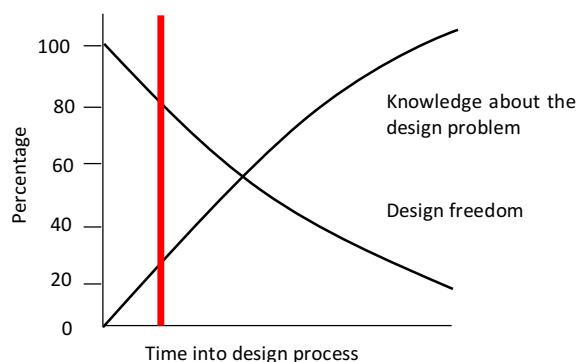


Figure 1. This paper focuses on the conceptual design phase (illustrated with the red bar) in which design freedom is still high, but the knowledge about the project in its entirety limited. In this phase, the design decisions may have high consequences for the performance of the completed project. Based on (Ullman, 2009, p. 19).

However, one could pose the question: by which criteria should the performance of e.g. a renovated dwelling be evaluated?

Stylsvig Madsen and Beim (2015) carried out a comparative study of eight evaluation methodologies with relevance for the Danish building renovation industry and found that the majority of the methodologies had an apparent emphasis on technical, quantifiable values. They then advocated for a need to include qualitative socio-cultural values in future evaluations in order to secure a holistic approach (Stylsvig Madsen and Beim, 2015, p. 39). This is supported by the Norwegian researchers Acre and Wyckmans, who state that "...the inattention to the potential of nontechnical dimensions such as spatial quality, by stakeholders involved in the energy renovation of dwellings, constitutes a lost opportunity to increase occupants' receptiveness to energy renovation." (Acre and Wyckmans, 2015, p. 12). Acre and Wyckmans (2015) as well as Hvejsel et al (2015) argue that the transformation towards a more energy-efficient building mass often involves radical changes to the existing built environment, which affect the perceived spatial quality (Acre and Wyckmans, 2014) (Stylsvig Madsen and Beim, 2015) (Hvejsel et al., 2015). But how do we proceed from here? How do we articulate these changes to spatial quality as part of a holistic approach to building performance evaluation and decision support in the early stages of a design process?

In the popular science publication “Arkitektur Energi Renovering” (Architecture, Energy Renovation), the authors proposed a “hands on” renovation guide for practicing consultants (Marsh et al., 2013). The guide is divided into three typologies: single-family houses, multi-storey dwellings and offices, and provides simple tools, suggestions for strategies and cases. In addition to energy optimization and indoor climate guidelines, the guide also articulates more “soft” renovation themes such as “Bedre rumlighed” (“improved spatiality”) but only to

a limited extent. The theme “spatial quality” therefore still appears to be less explicitly articulated than its more quantifiable counterparts such as energy performance (Marsh et al., 2013, p. 5) (Hvejsel et al., 2015, p. 37).

In this paper, we take the above-mentioned publications as our point of departure and begin to elaborate on how to further articulate the notion of spatial quality. The study reviews existing literature on the subject, including an analysis on how different architectural theoreticians have communicated their views - spanning from more loosely defined themes, over “rules of thumb” to metrics, which are more readily applicable for performance evaluation. We follow up on this by suggesting that metrics for articulating spatial quality can be established and subsequently made operational for design information and performance evaluation in the early design stages. Based on the literature review and a case study, the paper discusses the relevance of doing so in practice, and what we gain or lose when pursuing this approach.

## Methods

### ***Narrative literature review***

When aiming to evaluate spatial quality, we could study the users’ affective appraisal of the spaces in question, i.e. how the users experience the spaces they inhabit and how they describe that experience. Another way is to focus on identification of parameters (metrics) through existing literature (Acre & Wyckmans, 2014) (Olesen, 2014). In this study, we use the latter approach. Based on a literature study of four architectural theorist’s perspective on spatial quality, we aim to articulate examples of “metrics” within the topic of “spatial quality” and discuss if and how they can be operationalised for inclusion in building performance simulation tools.

Exploring the notion of spatial quality has been a theme of many a scholar and practitioner. This paper does not encompass an exhaustive account of the term “spatial quality” but rather aims to articulate what lies behind this term, focusing on its qualitative aspects. The selection process for including architectural theoreticians has been to include a span of definitions, ranging from more loosely defined spatial themes (e.g. Juhani Pallasmaa and Pierre von Meiss), over “rules of thumb” by e.g. Jan Gehl, to researchers with a quantitative approach as part of a qualitative evaluation system. We have only included literature with relevance for the dwelling scale and its immediate surroundings. Based on the literature review, the paper discusses the relevance of including and quantifying metrics related to spatial quality as an integral part of a holistic approach to low energy-building design and evaluating these through computer simulation.

In the paper “Towards a Holistic Approach to Low-Energy Building Design: Consequences of Metrics for Evaluation of Spatial Quality on Design” by Purup et al (2017), the examples of identified metrics from the present paper are included in computer simulations of design proposals for the renovation of a housing complex in Aarhus Denmark.

## Analysis

### ***Expanding the notion of spatial quality***

In table 1, we present an overview of parameters put forward by four architectural theoreticians in relation to “spatial quality”. To the right is an indication of the architects’ approach, ranging from a more intuitive qualitative approach to metrics intended for quantitative evaluation.

Table 1. Spatial quality in the eyes of architectural theorists.

	<b>Focus</b>	<b>Parameters</b>	<b>Approach</b> (spanning from an intuitive qualitative approach to metrics intended for quantitative evaluation)	<b>Method of inquiry</b>
<b>Acre &amp; Wyckmans</b> (Acre and Wyckmans, 2014)	Renovation of dwellings	<ul style="list-style-type: none"> <li>● Views</li> <li>● Internal spatiality and spatial arrangements</li> <li>● Transition between private and public spaces</li> <li>● Perceived human and built densities</li> </ul>		Litterature review
<b>Jan Gehl</b> (Gehl, 2003)	Outdoor spaces and transition spaces	<ul style="list-style-type: none"> <li>● To gather – or scatter</li> <li>● To integrate – or segregate</li> <li>● To invite - or reject</li> <li>● To open up – or enclose</li> </ul>		Field studies Literature review
<b>Pierre von Meiss</b> (von Meiss, 1990)	Architecure in general	<ul style="list-style-type: none"> <li>● Depth of space</li> <li>● Density of space</li> <li>● Openings</li> <li>● Spatial juxtaposition and interpenetration</li> <li>● Geometry of plan, sections and spaces</li> <li>● Light and shade</li> <li>● Floor, wall and ceiling (enclosure, demarcation, texture)</li> </ul>		Case studies Literature review
<b>Juhani Pallasmaa</b> (Pallasmaa, 1996)	Architecure in general	<ul style="list-style-type: none"> <li>● Multi-sensory experience</li> <li>● Shadow</li> <li>● Acoustics</li> <li>● Scent</li> <li>● Taste</li> <li>● Bodily identification</li> </ul>		Case studies Literature review

Table 1 illustrates the somewhat ambiguous notion of “spatial quality”. It also suggests that there are differences in the approaches of the included theoreticians. Meiss points out the “strings” of the instrument of architecture, which can be put into use, but refrains from establishing rules for how to play on it. Gehl puts forward “rules of thumb” based on observations from literature studies (Gehl, 2003). Acre and Wyckmans use references such as Gehl to establish a set of more generally applicable and quantifiable “rules”, which can ultimately be applied in an evaluation scheme, in which one can assess the consequences of renovation initiatives (Acre and Wyckmans, 2015). This, in turn, contrasts the more phenomenological, sensuous approach proposed by e.g. Pallasmaa (Pallasmaa, 1996).

### ***Exemplifying metrics for evaluation of spatial quality***

In the previous section, we have briefly outlined how four architectural theorists have communicated their views on the term “spatial quality”. We see that the represented theorists offer different types of “decision support” for the design process. In this section, we examine if we can further develop the themes towards more quantifiable metrics, which can

be made operational for building performance evaluation through computer simulation. The objective is to translate “spatial quality” themes of a more qualitative character into metrics. More specifically, we focus on the four following issues related to spatial quality: Thermal comfort, Daylight conditions, View quality, and Privacy. The four issues (especially the two latter) are included as examples of how one could potentially include themes, which are traditionally treated more qualitatively as part of an argumentative design process. In the paper *“Towards a Holistic Approach to Low-Energy Building Design: Consequences of Metrics for Evaluation of Spatial Quality on Design”* by Purup et al (2017) the examples of metrics proposed in the present paper are further developed and included in simulations of design proposals for a renovation case. In the present paper, we shall limit ourselves to discussing the process of translating themes into examples of metrics applicable for computer simulation.

### *Thermal comfort*

Looking into comfort parameters in residential buildings, Frontczak et al (2011) found that 35 % of the 645 respondents answered, that temperature contributes to their comfort. Only light and sun was more influential (46%). In another survey among 1990 randomly chosen house owners in Furesø Kommune, Denmark, thermal comfort was mentioned as the third most important motivation for renovation (Knudsen, 2014). These studies indicate that thermal comfort is an important quality in housing. However, studies rarely correlate user answers to thermal measurements that can be transformed into metrics; even the well-known PMV-metric is not suitable for evaluation of thermal comfort in homes (Becker and Paciuk, 2008). A recent study of student houses in Aarhus, Denmark, seeks to correlate user votes and thermal measurements (Petersen et al, 2016), and find a slight correlation to the SCAT-model which relates the comfortable indoor temperatures to the outdoor temperature while assuming that occupants have adaptive behavior in terms of clothing level and opening of windows for cooling (Nicol and Humphreys, 2010). This evaluation model is also used in other research on thermal comfort in housing (Brotas and Nicol, 2016), and suggested as evaluation model for Danish residential (Petersen et al, 2014). Despite the lacking research-based evidence, the SCAT-model may be suitable for evaluation of thermal comfort in houses, and is proposed as a metric by the authors of this paper.

### *Daylight*

The importance of daylight to human well-being is widely recognized, e.g. by Volf (2013). As opposed to e.g. View quality and Privacy, the idea of quantifying “daylight quality” for the purpose of performance evaluation is not a novelty. In Denmark, the Building Regulations require a minimum glazed area corresponding to minimum 10 % of the interior floor area or a documented daylight factor of minimum 2 % in half of the room (Byggecentrum, 2016). Acre and Wyckmans suggest using daylight factor and sky view factor as a means to evaluate the daylight performance (Acre et al., 2015). Nabil and Mardaljevic (2006) proposed that UDI (Useful daylight Illuminance) should substitute the DF as a way to say more about the quality of the daylight. UDI can be defined as the percentage of the year when daylight illuminance on the work plane falls within a range from 100-2000 lux. Below 100 lux, artificial lighting is needed and above 2000 lux the illuminance level is likely to cause discomfort (Nabil and Mardaljevic, 2006). From a phenomenological perspective, such quantifications do not say much about the actual perceived quality of daylight (or shadow). Meiss argues that the changing character of light during the day contributes to a “*change in atmosphere’ which denotes a qualitative change in which quantity of light is of only secondary importance*” (von

Meiss, 1990, p. 121). Since it is the purpose of this study to propose metrics for quantification, we propose the UDI as a way to proceed. However, the brief elaboration of the theme illustrates that it is essential to only use UDI as one of perhaps many indicators in a qualitative assessment of daylight conditions.

#### *View quality and degree of privacy through windows*

It is well recognized that the possibility to look out and observe nature and orient oneself in relation to time and place is important for human wellbeing (Hauge, 2013, p. 5) (VELUX, 2013, P. 8). On the other hand, the window also comprises a “social boundary” which makes it possible to remain private (Hauge, 2013, p. 47). In table 2, we revisit and expand the notions put forward by the architectural theorists listed in table 1 to discuss their different approaches to articulating ‘views’ and ‘privacy’ as themes within the architectural theoretical domain.

Table 2. Selected statements about views and privacy put forward by architectural theorists.

	<b>Example of statements related to view quality</b>	<b>Example of statement related to degree of privacy</b>
Acre and Wyckmans	<p><i>“Spatial quality assesment for views:</i></p> <p><i>2. Quality of the view (composition of the view)</i></p> <ul style="list-style-type: none"> <li>a) <i>Distance of the view (depth) is &gt; 6 m (yes or no question)</i></li> <li>b) <i>Width of the view through window(s) is &gt; 28_ (yes or no question).</i></li> <li>c) <i>Presence of layers of proximity (sky, landscape and ground) (yes or no question)”</i> (Acre and Wyckmans, 2015, p. 15)</li> </ul>	<p><i>“(C) Distance and degree of sight protection (visual privacy and protection of the private domain)</i></p> <p><i>1. View of arriving visitors and entrance, and entry-lock (hall) to the dwelling</i></p> <ul style="list-style-type: none"> <li>a) <i>Possibility to see arriving visitors (yes or no question)</i></li> <li>b) <i>Possibility to see arriving visitors without being seen (yes or no question)”</i> (Acre and Wyckmans, 2015, p. 15)</li> </ul>
Gehl	<p><i>“Many details of the building, the outdoor areas and the entrance, can influence the use of the outdoor spaces”... “The bench by the entrance, sheltered from the rain and wind and with a nice view to the access road, is a modest, yet obvious way to support the life between the houses.”</i> (Gehl, 2003, p. 179)</p>	<p><i>“The houses were placed 3-4 m from the pavement, far enough to secure a certain level of privacy in the area in front of the house – to keep the activities at an arm’s length.”</i> (Gehl, 2003, p. 181)</p>
von Meiss	<p><i>“The degree of enclosure does not only depend on the quantity and the size of the openings. When we wish to create a space which tends to open to the exterior, we are trying to make it less explicit”... “The larger theese openings become the more they designate an absence of wall.”</i> (von Meiss, 1990, p. 107f)</p>	<p><i>“The space of the window is a potential privilaged place in the room. Its transparency, the direct light and sun which enters it, invite and encourage particular activities: to sit near the window and follow the comings and goings outside without beeing seen.”</i></p> <p>(von Meiss, 1990, p. 152)</p>
Pallasmaa	<p><i>“In our time, light has turned into a mere quantitative matter and the window has lost its significance as a mediator between two worlds, between enclosed and open, interiority and exteriority, private and public, shadow and light. Having lost its ontological meaning, the window has turned into a mere absence of the wall.”</i></p> <p>(Pallasmaa, 1996, p. 47)</p>	

We see from table 2 that the included theoretical statements span from discussions about the window from an ontological and phenomenological perspective (Pallasmaa, 1996)

(von Meiss, 1990) to more concrete guidelines for how to practically deal with this threshold (Gehl, 2003) and an actual “check list” provided by Acre and Wyckmans (Acre and Wyckmans, 2015). In testing metrics for application in computational simulation, we lean on the latter approach. Acre and Wyckmans suggest an approach to view quality through windows based on “yes/no” questions. This offers a means to compare different alternatives in a similar way, yet the metrics must be further elaborated for implementation in computer simulation. For evaluation of view quality through windows, we suggest establishing an expression “View-out quality” that takes into account the extent of the potential view to the exterior through the proposed windows and a weighing of the elements that constitute the view. For evaluation of “Degree of privacy”, we suggest an expression based on the complementary percentage of the view potential and a weighing of areas in the exterior, which represent a risk of views to the interior. In the proposed examples of metrics, we focus on the performance in the interior space. As such, we do not address the view quality or degree of privacy in relation to private outdoor spaces (Gehl, 2003) (Acre and Wyckmans, 2015). For further elaboration of the proposed metrics, see Purup et al (2017).

## **Discussion and conclusion**

In the previous chapter, we have listed examples of metrics for “View-out quality” and “Degree of privacy” related to alteration of the building envelope. In this section we engage in a brief discussion about the relevance of including metrics for evaluation of spatial quality in building performance evaluation through simulation. In relation to renovation of existing social housing, we see a potential in the use of the metrics to articulate the more “soft” values alongside the “hard” values in a more equal manner, which can ultimately lead to different design choices compared to design decision based on “hard” values only. For an experienced architect, it may not be surprising that one solution may offer a better view than another does. However, when graphically displaying the quantitative outcomes of the simulations related to e.g. daylight and view alongside the results related to energy consumption, we may be more inclined to accept design solutions in interdisciplinary design teams, which have slightly reduced performance in terms of energy consumptions, but performs significantly better in terms of daylight and view quality. However, we do not see this approach as a replacement of the creative argumentative process. The architect must still evaluate the results relative to the expected activities within the space and with a specific user group in mind. Seen from a phenomenological perspective, in this study represented by e.g. Pallasmaa (1996), the spatial experience cannot be understood separately through quantification of single components, but must be understood as a totality, as it is experienced by a subject through bodily encounters (Pallasmaa, 1996). An example, where the quantitative metrics on “View-out quality” and “Degree of privacy” may be insufficient for a holistic performance evaluation is that they do not account for aspects such as “ambience” (von Meiss, 1990, p. 121), “material encounters” (Pallasmaa, 1996) (Rasmussen, 1966) or the ability for people to personalize the windowsill with “knick-knack” (Hauge, 2013, p. 8) when e.g exploring façade solutions scenarios. What we are merely suggesting is that quantifying some of the qualities related to spatial quality may establish a shared language for equal evaluation of both “soft” and “hard” metrics in the early stage of the renovation process.

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## References

- Acre, F. & Wyckmans, A. (2014). Spatial quality determinants for residential building renovation: A methodological approach to the development of spatial quality assessment. *International Journal of Sustainable Building Technology and Urban Development*, 5, 183-204.
- Acre, F. & Wyckmans, A. (2015). Dwelling renovation and spatial quality: The impact of the dwelling renovation on spatial quality determinants. *International Journal of Sustainable Built Environment*, 4, 12-41.
- Becker, R. & Paciuk, M. (2008). Thermal comfort in residential buildings – Failure to predict by Standard model. *Building and Environment* 44 (2009) 948–960.
- Brotas, L. & Nicol, F. (2016). Using Passive Strategies to prevent overheating and promote resilient buildings. In: P. LaRoche and M. Schiler, *The 32nd International Conference on Passive and Low Energy Architecture*. Los Angeles, 11.-13. July 2016, Volume I, Los Angeles: PLEA 2016
- Byggecentrum (2016). *Bygningsreglement 2015* (BR 15). The Danish Transport, Construction and Housing Authority.
- Churchman, C. W. (1967). Wicked Problems. *Management Science*, 14, B-141-B-146.
- European Commission (2016). *Eurostat*. Available: <http://ec.europa.eu/eurostat>. [Accessed 30 03 2016].
- Frontczak, M. & Andersen, R.V. & Wargocki, P. (2011). Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. *Building and Environment* 50 (2012), 56-64.
- Gehl, J. (2003). *Livet mellem husene: udeaktiviteter og udemiljøer*, Arkitektens Forlag.
- Government (2014a). *Strategi for energirenovering af bygninger: Vejen til energieffektive bygninger i fremtidens Danmark*. Danish edition ed.: The Danish Government.
- Government (2014b). *Strategy for energy renovation of buildings: The route to energy-efficient buildings in tomorrow's Denmark*. English edition ed.: The Danish Government.
- Hauge, B. (2013). *Vinduets betydning - en kvalitativ, antropologisk undersøgelse af hvad vinduet gør for folk*. Report. DTU.
- Hvejsel, M. F., Kirkegaard, P. H. & Bundgaard, S. (2015). Towards a Tectonic Approach. *Nordic journal of architectural research*, 27, 35-60.
- Knudsen, H. & Kragh, J. (2014). *Evaluering af energiklasserne 2015 og 2020 i BR10. SBi 2014:07* (in Danish).
- Marsh, R., Faurbjerg, L. M., Kongebro, (2013). *Arkitektur energi renovering : designguide for energi-, dagslys- & indeklimarenovering*, Kbh: Danish Building Research Institute (SBI).
- Nabil, A. & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38, 905-913.
- Nicol, F. & Humphreys, M. (2008). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, 45 (2010), 11-17.
- Pallasmaa, J. (1996). *The Eyes of the Skin: Architecture of the Senses*, Wiley.
- Rasmussen, S. E. (1966). *Om at opleve arkitektur*, Fonden til Udgivelse af Arkitekturværker, Aarhus School of Architecture.
- Petersen, S. & Clausen, A.H. & Knudsen, L.D.S. (2016). Investigating the Ability of Prevailing Thermal Comfort Models to Predict Thermal Comfort inn Homes. In: P. Heiselberg, *CLIMA Conference 2016*. Aalborg, 23th-25th May 2016, Aalborg University
- Petersen, S. & Lauridsen, P.K.B. & Jensen, K.L. (2014). *Analyse af krav til termisk indeklima i BR15*. Energistyrelsen (in Danish).
- Purup, P.B., Jensen, S.R., Kirkegaard, P.H. & Petersen, S. (2017). *Towards a Holistic Approach to Low-Energy Building Design: Consequences of Metrics for Evaluation of Spatial Quality*. In: PLEA, Passive Low Energy Building Conference 2017. Edinburgh, 3th-5th July 2017, Edinburg, PLEA
- Statistics Denmark (2016). *Statistisk Årbog 2016*. 120<sup>th</sup> Edition. Copenhagen: Rosendahls.
- Styrlig Madsen, U., Beim, A. (2015). *Værdiskabelse i Bygningsrenovering: en minianalyse af udvalgte Koncepter for vurdering af egenskaber og kvaliteter i byggeri*. København: CINARK ( Kunstakademiets Arkitektskole).
- Olesen, G. G. H. (2014). *A Model for Enquiry of Sustainable Homes: of Model Home 2020*. PhD. Aalborg University.
- Ullman, D. (2009). *The Mechanical Design Process*, McGraw-Hill Education.
- VELUX (2013). *Circadian House: Principles and guidelines for healthy homes*. Denmark: VELUX.
- Volf, C. (2013). *Lys, arkitektur og sundhed - en metode*. PhD. Aarhus School of Architecture.
- Von Meiss, P. (1990). *Elements of Architecture: From Form to Place*, E & FN Spon.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Investigation the impact of students background on their thermal perception at higher education building

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**Abstract:** The quality of educational buildings can considerably affect teaching and learning processes. Literature shows that there is a significant relationship between students' thermal perception and their performance. The UK higher education buildings host many students from all over the world who have diverse backgrounds, perceptions and preferences toward their learning environment. The existing standards for optimum internal thermal condition in higher education learning environments consider students thermal sensation and requirement in a typical learning environment without addressing the impact of students' background. This study aims to evaluate students' thermal sensation and preferences in an architecture studio at Coventry University during heating season of 2016 with reflation to their background. The result from 110 questionnaires, which are filled by students at the same time with temperature measurement inside the space, reveals that students' background and cultural differences can influence on students thermal sensation. The outcome of this research provides better understanding about students' thermal requirement in higher learning environments with relation to their background. This result will help the Building Management System (BMS) to control the learning environment with relation to students' perceptions which results in improving students' productivity and wellbeing.

**Keywords:** Thermal comfort, Background, Learning environment, Higher education building

### Introduction

Thermal quality of learning environments can affect students' and lecturers' productivity, health and wellbeing. The excellence of interior thermal condition in such spaces influences occupants' physical, mental and psychological health which may affect the teaching and learning performance. (Tanabe et al. 2007, Zomorodian, et al. 2016, Barrett et al. 2015, Hassanain and Iftikhar 2015).

UK is committed to reduce its greenhouse gases emissions by at least 80% by 2050, relative to 1990 levels (climate change act, 2008) which have implication on the amount of energy that should be consumed for providing thermal comfort within learning environment. For this reason, a practical thermal guideline for adult learning environment is required which not only can support students' productivity and well-being, but also can save energy within the space and considerably reduce the building running costs. Statistics show that UK every year hosts a large number of students from other countries, both European and non-European. Almost 20% of the students studying in the UK higher levels are from out of this country, 6% EU and 14% non- EU (HESA, 2017). Students' various geographical, climatic and cultural backgrounds may lead to differences in their clothes, behaviour, cognitive and

finally thermal perception which causes a serious challenge in proving their thermal comfort in such multicultural spaces. Dissimilarity in their ages and genders can be another reason of their different thermal requirements (De Carli et.al. 2007, Kwon et.al, 2012). Digitalization and increasing the application of technological devices increase indoor air temperature (Jenkins, et.al. 2009) and may disrupt the space thermal balance.

Culture is defined by Reber (1985) as "The system of information that codes the manner in which people in an organized group, society or nation interact with their social and physical environment." (Reber, 1985, p. 170) people from a culture learn some standards, rules and regulations affecting their act, communication, belief, perception and evaluation. (Eisler et al. 2003). Culture origins which include climatic background can affect students' thermal perception as well (Kenawy, 2013). In addition to the mentioned factors, occupants' thermal history and expectation influence their thermal comfort in an environment. Thermal experiences can establish a memory, named habit, psychological adaption that influence individual sensation in a new environment, by comparison the space with the past experiences (Ji et al. 2017). People thermal comfort is highly related to their long term thermal history (Chun et. al, 2008, Luo et. al, 2016). According to importance of students' thermal comfort, their various thermal requirements should be considered in developing appropriate standards, which helps to have more satisfactory thermal condition in line with having energy efficient spaces. Existing literature in this field, mostly, focus on influence of environmental factors and occupants' physiological differences on thermal comfort and there are limited studies about the impact of psychological parameters on people thermal sensation. In this study the influence of students' climatic background, thermal condition of their living environments, clothing factor and location within the room on students' thermal sensation are investigated.

## Methodology

This survey was conducted in a naturally ventilated architecture studio at Coventry University in September 2016. 44 architecture undergraduate students, 20 males and 24 females, aged between 18 and 23 years old attended the studio in a weekday 10:30 am to 11:30 am, with partly cloudy sky condition. Students were from different countries, both European and non-European countries. Details for participants' climatic background can be seen in table 1.

The studio was in naturally ventilated condition. Five top hung windows (open for almost 10 cm) with approximately 80 cm length and 60 cm width allowed students to adjust the environment to restore their comfort.

Environmental monitoring consisted of recording indoor air temperature, relative humidity and CO<sub>2</sub> concentration by using two 'Extech SD800 CO<sub>2</sub>' loggers with time steps of 1 minute and accuracy of ± 40 ppm (<1000 ppm) and ± 5% rdg (> 1000 ppm) for CO<sub>2</sub> concentration, ± 0.8 °c for temperature and ± 4% for air RH. Loggers placed on carts 90cm above Fixed Floor Level (FFL), a CO<sub>2</sub> meter positioned in the higher and another in the lower level of trolley. Most equipment was at the rear of the room to avoid influence of windows. Classroom was divided into 4 different zones; a simple map is represented in figure 1, to assess impact of room layout on occupants' thermal perception. To prevent influence of clothing, students with almost similar clothing value are considered in this evaluation. To consider the impact of climatic background and thermal condition of living environments (before moving to Coventry) on students' current thermal comfort in the classroom, their

Thermal Sensation Vote (TSV) in the studio, climate of their hometown and thermal condition of their previous accommodation were collected through a questionnaire.

Questionnaire was filled at the same time of environmental monitoring. The questionnaire were divided into three sections including individual questions (such as age, gender, worn clothes), thermal comfort (thermal sensation vote in the studio, thermal condition of their home and climatic background) and overall thermal experience in the space. The questions are designed based on ISO 7730, (2005) guideline. Answer is provided by using a 5 points thermal sensation scale from 1 (Too cold) to 5 (Too warm). Questions for clothing are developed based on the mentioned guideline as well.

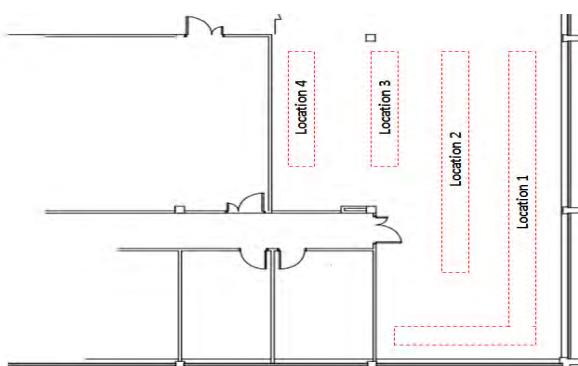


Figure 1, Studio layout during the experiment

### **Result analysis and discussion:**

The final results for the measured variables and conducted survey are divided into two main sections; Environmental factors and Students' thermal comfort votes.

#### ***Environmental factors measurements***

Result for outdoor air evaluation on the day of the experiment shows the minimum, maximum and average temperature for 10°C, 18°C and nearly 15°C respectively. During the experiment outdoor temperature started at 15.00°C and increased to 15.6°C by the end of the period. Outdoor air humidity level started at 75% and decreased to 68% by the end of the test. Regarding the indoor air condition, recorded temperature and humidity are illustrated in figure 2 and 3. Indoor air temperature faced a negligible increase during the experiment and its value stays in the acceptable range 19°C- 21°C according to CIBSE A (2015). Indoor air relative humidity can be considered mostly in the acceptable range, 40%-70% according to ASHRAE (2007), during the survey.

#### ***Students' thermal comfort votes***

Most of the participants in this survey are from UK, almost 68%, and about 32% of them are from other countries. There are international students from Romania, Italy, UAE, Bulgaria, Moldova, Zimbabwe, Indonesia and Nigeria with both colder and warmer climate compared to Coventry. Table 1 shows subjects' thermal background; majority of them (47.5%) are from warmer, 40% of them are from the same and 12.5% of them are from colder background compared to Coventry.

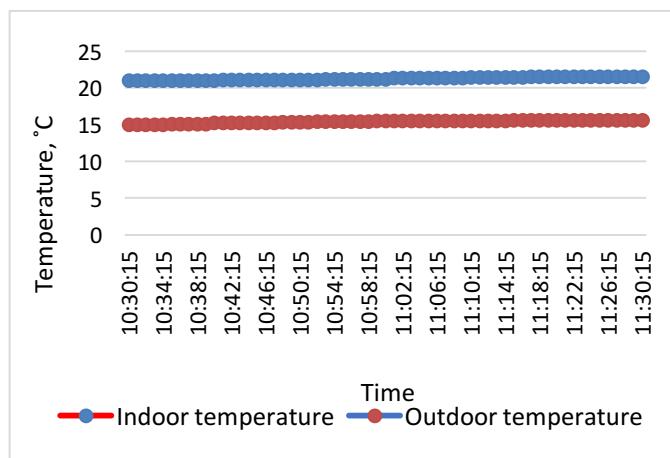


Figure 2, Indoor and outdoor air temperature during the experiment

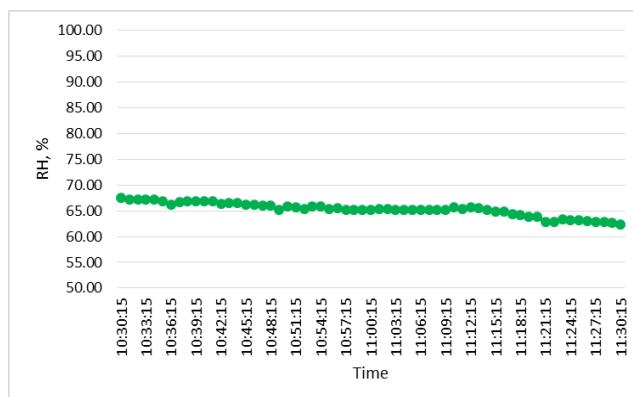


Figure 3, indoor air relative humidity during the experiment

Table 1, Subjects thermal background details

Country	Number of respondents	Climate	Summer temperature range	Winter temperature range
UK	30	Temperate	7_18 °C	-1_9 °C
Romania	6	Continental	18_22 °C	-2_5 °C
Nigeria	1	Tropical hot	25_28 °C	24_26 °C
Italy	1	Mediterranean	21_26 °C	6_10 °C
Zimbabwe	1	Tropical	32_38 °C	12_24 °C
Moldova	1	moderately continental	22_26 °C	-6_3 °C
UAE	1	Hot	35_43	20_27 °C
Bulgaria	2	temperate-continental	16_26 °C	-2_4 °C
Indonesia	1	Tropical	22_31 °C	22_29 °C

#### *Students' TSVs based their climatic background*

Figure 4 represents students' TSV in the classroom based on their climatic background. Considering students from warmer background compared to Coventry shows that 25.6 % of them feel warm in the classroom, 5.1 % feel neutral and 15.4 % feel cold in the studio. Students from colder climate than Coventry, 7.7 % feel cold, 5.1 % feel warm.

#### *Students TSVs based on their home country*

Thermal background and TSV in the studio for the UK students are illustrated in figure 5. Most of students have similar thermal sensation in the classroom and their hometown. 14% of students with colder background feel cold and 4% feel warm in the studio. 28.5% of students with warmer background feel warm and 9.5% feel cold in the studio.

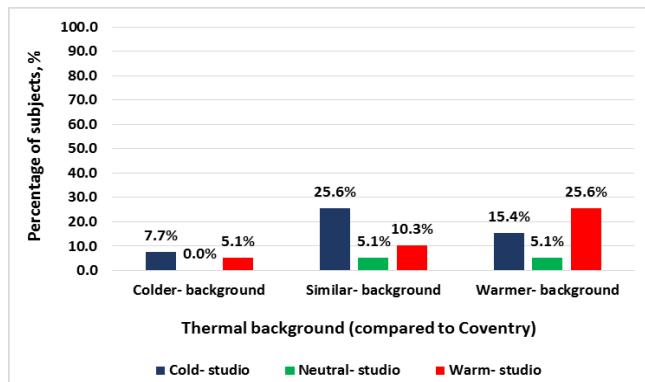


Figure 4, students TSV at studio based on their climatic background

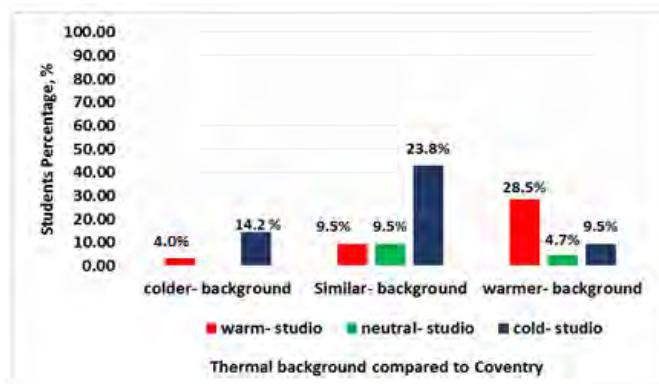


Figure 5, UK students TSV at studio based on their climatic background

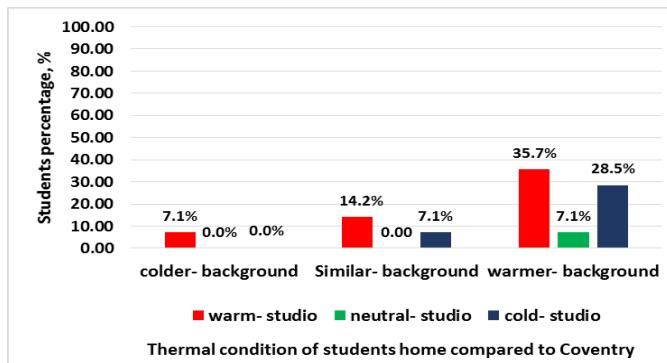


Figure 6, International students TSV at studio based on their climatic background

According to thermal history and expectation theory it is expected to find a reliable trend for the students' climatic background and TSV in the classroom. Statistical analyses show that there is a positive correlation between the UK students' thermal sensation in the classroom and thermal background. In other words, students with warmer background feel warm and others with colder background feel cold in the university studio ( $N= 21$ ,  $P= 0.011 <0.05$ , correlation coefficient= 0.52). Figure 6 indicates thermal sensation vote for international students coming from various climatic, geographical and cultural backgrounds. Most of participants from warmer climates feel warm in the university (35.7%), 28.5% of them feel cold and 7.1% feel neutral. All the students from colder background feel warm in the university. The statistical analysis of results for this section does not show a clear correlation between participants thermal background and TSV in the studio ( $N= 14$ ,  $P= 0.42 >0.05$ , correlation coefficient = - 0.2). The main reason for the poor correlation can be low number of collected data for this evaluation ( $N= 14$ ).

### **Subjects clothing value and thermal sensation in the studio**

Results for the UK and international students clothing value is summarized in table 2. Mean of clothing value is calculated for each group. This figure for students with neutral thermal sensation in the classroom (for either colder or warmer background) is considered as the benchmark. Comparing the students clothing value with the identified benchmark shows the reason of subjects' cold or warm thermal sensation in the studio. As there is no one with cold thermal background, neither from UK nor other countries, and neutral TSV in the classroom, no reasonable benchmark could be introduced for this group. Also, due to the low number of subjects with colder thermal background and cold thermal sensation in the current location (only 2 people) influence of clothing factor for them cannot be compared with other groups.

Table 2, UK and international students mean clothing value, thermal background and TSV at studio

<b>UK students</b>		
<b>Thermal background compared to Coventry</b>	<b>Students TSV in the studio</b>	<b>Mean clothing value</b>
Warmer	Warm	0.82
Warmer	Neutral	0.48
Warmer	Cold	0.6
<b>International students</b>		
Warmer	Warm	1.37
Warmer	Neutral	0.4
Warmer	Cold	0.85

Most of students in both UK and International groups are from warmer background and warm thermal sensation in the studio. UK students with warmer background and *warm* TSV in the classroom, in average have garments with 0.82 clo value. While, this figure for students with the same background and *neutral* and *cold* thermal sensation in the studio equals to 0.48 and 0.21 clo respectively. Clothing value for the UK students with both *cold* and *warm* thermal sensation votes in the studio is higher than the identified index.

Regarding the international students, mean clothing value for subjects with warm background and *warm* TSV in the classroom equals to 1.37 clo. This shows a much higher value compared to others from the same background with *neutral* or *cold* TSV in the classroom, 0.40 and 0.85 clo respectively. A reason for high level of clothing among the UK and international students with warm TSV and warm background can be due to their cold thermal perception in Coventry in the previous days. As most of students have moved to Coventry for less than 1 week, they may not be adapted to the weather and still may be affected by climate condition of their hometown. Therefore, the result in this section can support the theory of thermal history and expectation implying that cold or warm thermal background causes warmer or colder thermal perception in the new environments respectively. Students with cold thermal sensation have higher clothing value than the benchmark, but they still feel cold in the classroom. This again can be due to their warmer thermal history and cold sensation in current location. Higher clothing value for both UK and international students from warm background shows their cold thermal sensation in Coventry. It can be concluded that participants' with warmer thermal history feel colder compared to others with colder or similar backgrounds in a new environments. Higher level of clothing for this group is to adjust themselves to restore comfort.

### **Influence of interior thermal experiences on students TSV**

Climatic background cannot be the only factor affecting people thermal history and TSV in a building. Statistics show that people in developed country spend approximately 90% of their time inside a building (Harrison,et.al. 2002). Therefore, thermal condition of interior environments people exposed to may influence their thermal sensation in the new locations. Furthermore, it is proved by Yu (2013) that interior thermal experiences affects occupants' thermal sensation and tolerant in the new environments more than their climatic background. A reason is due to their longer exposure time to interior spaces than outdoor air. In this experiment TSV for students in both groups are evaluated by considering their interior thermal experiences and thermal condition of their living environments before moving to Coventry. This evaluation can justify another reason of the positive correlation between students TSV in the classroom and their climatic background. Figure 7 represents percentage of students with warm or cold TSV in the classroom based on thermal condition of their previous living environment. Overall, 62% of students feel cold in the studio and 29% of these students (almost half of them) experienced mechanically heated buildings before. 38% of participants feel warm in the studio and 10% of them were exposed to mechanically cool living environments before moving to Coventry.

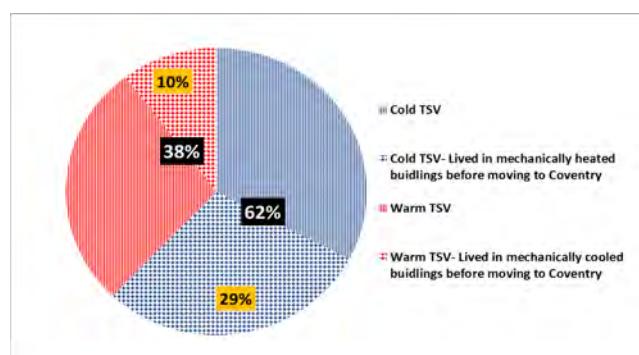


Figure 7, Students; TSV in the classroom and thermal condition of their previous living environments

This consideration, regardless of subjects' climatic background, indicates the significant impact of interior thermal experiences on students TSV in the classroom. Even, in this study, it is shown that interior thermal condition may affect subjects TSV in the new environments much more than their climatic backgrounds.

Table 3, percentage of students with warm, neutral and cold TSV in each zone

Zone	Students with warm TSV		Students with neutral TSV		Students with cold TSV	
	TSV	TSV	TSV	TSV	TSV	TSV
1 (next to windows)	37 %		45 %		18 %	
2 (middle)	33 %		67 %		0 %	
3 (middle)	80 %		0 %		20 %	
4 (far from window)	25 %		63 %		12 %	

### **Influence of room layout on subjects TSV**

Result for analysing students' TSV in each zone in the classroom is summarized in table 3. In general the majority of students seating in zone 3 feel warmer compared to other locations of the classroom. Zone 2 seems to be slightly warmer than others as there are all the

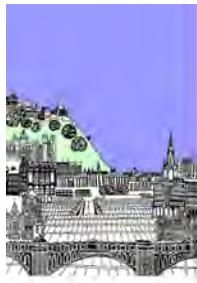
students seating here feel warm or neutral. This part of study shows the impact of location within a learning environment on students' thermal sensation.

### Conclusion and recommendation

This study investigates the influence of climatic background on students' thermal sensation in an architecture studio at Coventry University. Results show that occupant's thermal history including both interior thermal experiences (heated or cooled living environments) and climatic background can influence their thermal sensation in the new environments. Also, a negative correlation between subjects' thermal experiences and current thermal sensation inside the university studio is indicated. This findings can support the theory of thermal history, expectation and thermal adaption. The other output from this investigation is the impact of a space layout and occupants' location on their thermal sensation inside a building. It is illustrated that students seating in the middle of the room tend to feel warmer than others next to the wall.

### References

- Barrett, P., Davies, F., Zhang, Y. and Barrett, L. (2015) 'The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis', *Building and Environment*, 89, 118-133.
- Chun, C., Kwok, A., Mitamura, T., Miwa, N. and Tamura, A. (2008) 'Thermal diary: Connecting temperature history to indoor comfort', *Building and Environment*, 43(5), 877-885.
- De Carli, M., Olesen, B. W., Zarrella, A. and Zecchin, R. (2007) 'People's clothing behaviour according to external weather and indoor environment', *Building and Environment*, 42(12), 3965-3973.
- Eisler, A. D., Eisler, H. and Yoshida, M. (2003) 'Perception of human ecology: cross-cultural and gender comparisons', *Journal of Environmental Psychology*, 23(1), 89-101.
- Harrison, R M ; Thornton, C A ; Lawrence, R G ; Mark, D ; Kinnersley, R P ; Ayres, J G. (2002) ' Personal exposure monitoring of particular matter, nitrogen dioxide, and carbon monoxide, including susceptible groups', *Journal of Occupational and Environmental Medicine*, 59(10), p.671- 679  
*Environmental Medicine*, 59(10), p.671- 679
- Hassanain, M. A. and Iftikhar, A. (2015) 'Framework model for post-occupancy evaluation of school facilities', *Structural Survey*, 33(4-5), 322-336.
- INJI KENAWY, H. E. (2013) 'The impact of cultural and climatic background on thermal sensation votes', in *PLEA Conference - 29th Conference, Sustainable Architecture for a Renewable Future*, Munich, Germany
- Jenkins, D.P, Peacock, A.D, Banfill, P.F.G. (2009), 'Will future low-carbon schools in the UK have an overheating problem?', *Building and Environment*, 44, 490– 501Ji, W., Cao, B., Luo, M. and Zhu, Y. (2017) 'Influence of short-term thermal experience on thermal comfort evaluations: A climate chamber experiment', *Building and Environment*, 114, 246-256.
- Kwon, J. and Choi, J. (2012) 'The relationship between environmental temperature and clothing insulation across a year', *International Journal of Biometeorology*, 56(5), 887-893.
- Luo, M., de Dear, R., Ji, W., Bin, C., Lin, B., Ouyang, Q. and Zhu, Y. (2016) 'The dynamics of thermal comfort expectations: The problem, challenge and implication', *Building and Environment*, 95, 322-329.
- Montazami, A., Gaterell, M. and Nicol, F. (2015) 'A comprehensive review of environmental design in UK schools: History, conflicts and solutions', *Renewable and Sustainable Energy Reviews*, 46, 249-264.
- Nikolopoulou, M. and Steemers, K. (2003) 'Thermal comfort and psychological adaptation as a guide for designing urban spaces', *Energy & Buildings*, 35(1), 95-101.
- Reber, A. S. (1985) *The Penguin dictionary of psychology*, Viking.
- Tanabe, S.-I., Nishihara, N. and Haneda, M. (2007) 'Indoor Temperature, Productivity, and Fatigue in Office Tasks', *HVAC&R Research*, 13(4), 623-633.
- Yu, J., et al., People who live in a cold climate: thermal adaptation differences based on availability of heating. *Indoor Air*, 2013. 23(4): p. 303-310.
- Zomorodian, Z. S., Tahsildoust, M. and Hafezi, M. (2016) 'Thermal comfort in educational buildings: A review article', *Renewable and Sustainable Energy Reviews*, 59, 895-906.
- UK regulations: the climate change acts (2008), Committee on climate change



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainable Renovation Framework: Introducing three levels of Integrated Design Process Implementation and Evaluation

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**Abstract:** Future sustainable building renovation is a balance between the economic and environmental impacts related to the desired social activities facilitated by the renovated building. A review of recent research has revealed that the present efforts on sustainable objectives fulfilment in renovation projects are not sufficient. This paper investigates processes and frameworks in building renovation. It aims to deal with simplification of the existing complexity due to involvement of various types of stakeholders, sustainability criteria and potential renovation technologies in design process. Moreover, it facilitates understanding of the design process implementation through identification of the different activities, which need to be carried out. Hereafter, two frameworks by application of different Multiple Criteria Decision Making (MCDM) methods are developed and for each one, three levels of decision-making and the required activities are provided. Finally, the decision-making at the third level is considered as a scientific design approach and is introduced as an integrated design process implementation and evaluation for the use of sustainability value-oriented criteria in design process. It helps stakeholders in the renovation process to discuss their project “on the same level” and results to make transparent decisions in a rational order.

**Keywords:** Building renovation, Decision making, Sustainability, Multiple Attribute Decision Making (MADM), Multiple Objective Decision Making (MODM)

### Introduction

Renovation of existing buildings is currently achieving increased attention in different European countries (Jensen and Maslesa, 2015). The reason is that buildings are responsible for the largest untapped potential for cost effective energy saving and CO<sub>2</sub> reduction potential (BPIE, 2013). This potential was quantified by the European Commission [EC] (2014) to be about 40% of total energy consumption and 36% of CO<sub>2</sub> emissions in the European Union. However, increasing energy efficiency and reducing carbon emission are often not the only goals in building renovation projects. Projects may benefit from adopting a more broad approach to sustainability which seeks to decrease operation and maintenance costs; reduce environmental impacts; and can increase the building's adaptability, durability, and resilience towards future challenges. Consequently, the building may be less costly to operate, may grow in value, last longer, and contribute to a preferable, healthier, more convenient environment to the occupants (Kamari et al, 2017b).

There may be various reasons for why an existing building is to be renovated, and consequently different degrees of how extensive the renovation is. Common reasons for

renovation is a need for general upgrading, functional changes and additions, replacement of equipment, and/or improving comfort (Burton, 2012). When all of these interventions are summated, they can move the renovation case towards the goal of overall sustainability which demands new and more holistic design processes. As response to this, the Danish research project RE-VALUE<sup>1</sup> (Value Creation by Energy Renovation, Refurbishment and Transformation of the Built Environment, Modelling and Validating of Utility and Architectural Value) has been initiated to establish a more holistic approach to the assessment of value creation in building renovation projects. The present paper builds upon previous work by the authors towards a holistic approach to carry out a sustainable retrofitting (Kamari et al, 2017a). In this work, a HMSR (Holistic Multi-methodology for Sustainable Retrofitting) was developed which aims to deal with the complexity and “soft” nature of the retrofitting problem involving different decision makers with different priorities. As the result of this effort, a multi-methodology based on mixing certain Soft Systems Methodologies (SSM) with Multiple Criteria Decision Making (MCDM) methods including eight steps was developed. Furthermore, a new sustainability framework to audit, develop and assess building renovation performance and to support informed decision-making throughout the project's life cycle was developed. This previous research was inspired by a number of sustainability assessment methodologies (Jensen et al, 2016) using SSM (Checkland, 2000) and Value Focused Thinking (Keeney, 1992). The product was a Value Map consisting of three categories – *Functionality, Accountability, and Feasibility* – with a total of 18 sustainable value-oriented criteria (Kamari et al, 2017b).

The research study of this paper intends to match the HMSR to the Value Map, and articulate different levels of decision-making throughout the process. Introducing these levels will facilitate understanding of the design process implementation through identification of the different activities, which need to be carried out. The paper evolves around the process of generating renovation scenarios<sup>2</sup> and selection of different renovation technologies/actions. The paper therefore outlines two typical decision-making frameworks which uses two different types of decision-making methods, in order to 1) ensure that the proposed levels will deal with the existing complexity in the process, 2) outline a systematic approach that includes the typical activities of an integrated renovation design process, and 3) encompass the different levels of decision-making where issues related to alternative renovation solutions must be agreed on. Finally, each of the two frameworks is divided into the proposed three levels: *Exploration, Assessment and Scientific Decision-making*. In this perspective, the research in section 2 investigates the notion of decision-making for building renovation and provides information about two different MCDM approaches. Later in section 3, it represents two frameworks including three steps of integrated design process implementation and evaluation for building renovation. Further, it discusses that a decision can be made at the end of each of the three steps and hence it defines three levels of decision-making process based upon the three stages. Finally, section 4 outlines a brief conclusion and possible future of the current research project.

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<sup>1</sup> Participated by Brabrand Housing Association – with energy renovation in the Aarhus suburb of Gellerup – as well as DEAS, an administration company on the private rental housing market (for more info: <http://www.revalue.dk>)

<sup>2</sup> The term “renovation scenario” used in this study means a selection and combination of some different renovation technologies/actions (i.e. insulation of the external walls or replacement of the windows are each a renovation action) that together build an alternative renovation scenario/package and subsequently is applied in a renovation project.

## Building renovation through a decision-making framework

Building renovation can be regarded as a problem-solving activity terminated by a solution deemed satisfactory. It is a type of action with a purpose or for a specific purpose. Therefore, it is a process that can be more or less rational, and based on explicit or tacit knowledge. From one perspective, the process can be regarded as a cognitive process resulting in the selection of a most appropriate renovation scenario, selected out of the set of  $m$  common standard scenarios, which usually is the case for experienced architects or design engineers or consultant companies. In order to evaluate the  $m$  number of standard scenarios,  $n$  number of criteria/objectives e.g. from the list of 18 identified criteria in Kamari et al. (2017b), will be shortlisted. Next, the pre-generated  $m$  number of standard scenarios is compared to the  $n$  number of criteria with the aim to select the most satisfactory scenario for the renovation project (see option "A" in Figure 1).

The improvement of existing buildings involves two major steps: current condition assessment and future upgrade strategies (Juan et al, 2010). Most of the methods focus on the first step of the improvement process, understanding or predicting energy usage but no generation of possible renovation scenarios. While the latter is about proposing of the future upgrade renovation strategies. In this process perspective, it is not a question of assessing standard renovation scenarios/packages but a process of developing scenarios for the individual renovation project bottom-up. In this case,  $i$  number of renovation actions will be identified and combined in order to make a ranking of the  $j$  number of building renovation scenarios. To this end, some objectives such as energy efficiency, water efficiency, cost etc. will be shortlisted and to some extent get enhanced by combination of the most fitted renovation actions (e.g. assuming two objectives as object 1 and object 2 as shown in option "B" in Figure 1). The goal can be to find a representative set of Pareto optimal solutions (Pareto, 1896), and/or quantify the trade-offs in satisfying the different objectives, and/or finding a single solution that satisfies the subjective preferences of a human decision maker. Using prospect of decision making for building renovation, both of the two options (A and B) demonstrated in Figure 1 are regularly being researched and used in practice. In order to proceed with the options, the research can find the roots in decision-making era where a decision is made by explicitly evaluation of multiple conflicting criteria [sustainability criteria] over various existing alternatives [renovation technologies].

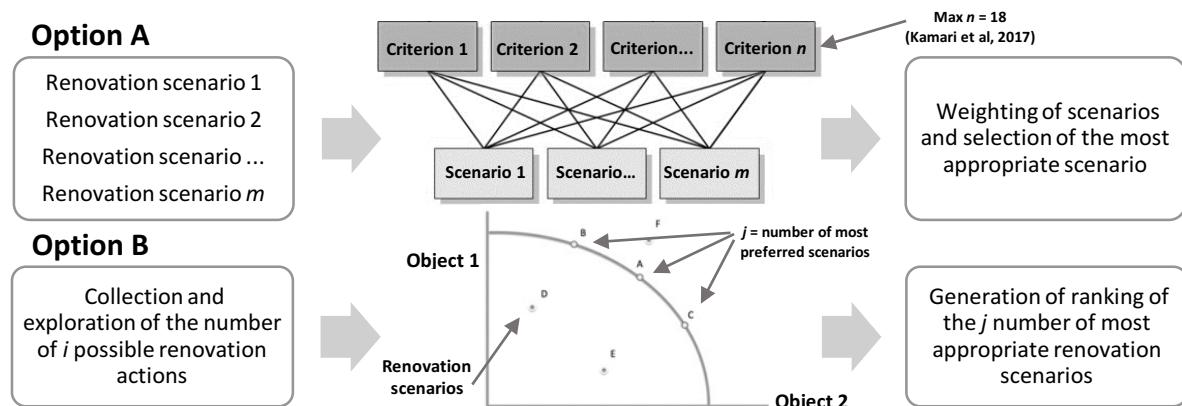


Figure 1. Building renovation throughout multiple decision-making frameworks

Hereafter and depends on working with either option A or B, different types of Multiple Criteria Decision Making (MCDM - Triantaphyllou et al, 1998) methods can be utilized. MCDM basically facilitates the process of resolving the trade-off between criteria (typically based on

the preferences of a decision maker) when a solution performs well in all criteria. MCDM have been categorized into different groups and methods (Wang et al, 2009). The more popular MCDM categories are Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM) (Climaco, 1997). MODM can be used for decision problems in which the decision space is continuous (option "B" in Figure 1) while MADM (option "A" in Figure 1) can be used for problems with discrete decision spaces (Triantaphyllou et al, 1998). Taha and Daim (2013) discuss that the decision problem in MADM is characterized by the evaluation of a set of alternatives against a set of criteria rather than, as in MODM, the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints. The Analytic Hierarchy Process (AHP) by Saaty (1980) is one of the most popular methods in MADM area. Similarly, for MODM area, Genetic Algorithms (GA) is regarded as an effective analytic tool and stochastic search technique to solve large and complicated problems using ideas from natural genetics and evolutionary principles (Juan et al, 2010).

### ***Sustainable Retrofitting Framework – Option "A" using MADM methods***

The option "A" shown in Figure 1, is related to processes which uses MADM decision-making methods, and hence the trade-offs among the criteria are estimated and addressed based on the interdependent relations among the selected criteria and renovation scenarios (Volvačiovas et al, 2013). For this reason, all the quantifiable criteria including quantitative and qualitative should also be converted to quantitative criteria using for instance "1-9" scaling system proposed by Saaty (1980), or "1-5" Likret scale (1932).

### ***Sustainable Retrofitting Framework – Option "B" using MODM methods***

The option "B" shown in Figure 1, is related to processes where decision-making includes considerations of all possible renovation actions and their trade-offs in order to generate an optimal solution. The criteria are selected, assessed and optimized by proposing a combination of the most appropriate renovation actions. It is similar to optimization problems in other domains (Ascione et al, 2015). For option "B", a Decision Support System (DSS) needs to be developed in order to assess the building conditions and to recommend an optimal set of sustainable renovation strategies upon consideration of the trade-offs between selected criteria (Juan et al, 2010). DSS have been a major research area in the Information Systems (IS) field. Petkov et al (2007) classified DSS field into (a) computer based automation of problem solving heuristics; (b) computer based model development and manipulation; (c) problem formulation in organizations. All of the three approaches can be considered useful for identifying a solution in option "B". The difference between the option "A" and "B" here is related to where the ranking of the renovation scenarios is made. Combining problem-solving algorithms from MODM with the principles of evolution, GA demonstrates great operations for combinatorial renovation solution optimization (Juan et al, 2010; Lee and Kim, 2007). However, it seems that all of the existing sustainability criteria cannot be addressed within a DSS, due to the soft nature of some of them (i.e. sociality, identity, spacial etc.). For this reason, and in order to address overall sustainability criteria within a successful renovation scenario, the DSS must be developed into a comprehensive design process in which the process is equipped by a mix of MCDM and SSM methods (Kamari et al., 2016a).

## Introducing three levels of Integrated Design Process Implementation and Evaluation

The discussions of options “A” and “B” in Figure 1 have led to the formulation of two different integrated design frameworks (see Figures 2 and 3). The main reason for development of such a framework is primarily to facilitate understanding of the design process implementation through identification of the different activities, which need to be carried out. Moreover, this also deals with simplification of the existing complexity due to involvement of various types of stakeholders, sustainability criteria and potential renovation technologies in design process. Consequently, the level of complexity for decision-making increases when trade-offs between design criteria and stakeholders priorities need to be addressed; the frameworks seeks to establish a platform for facilitating decision-making under these circumstances. Figures 2 and 3 hold information about the relevant activities for each proposed three level of decision-making. The framework in Figure 2 has been developed by the principles discussed as option “A” using MADM, and Figure 3 by the principles discussed as option “B” using MODM during previous section. Based on the types of the activities that need to be carried out for each level as well as how a decision is processed, they have been named as I) *Exploration*, II) *Assessment* and III) *Scientific Decision-making*.

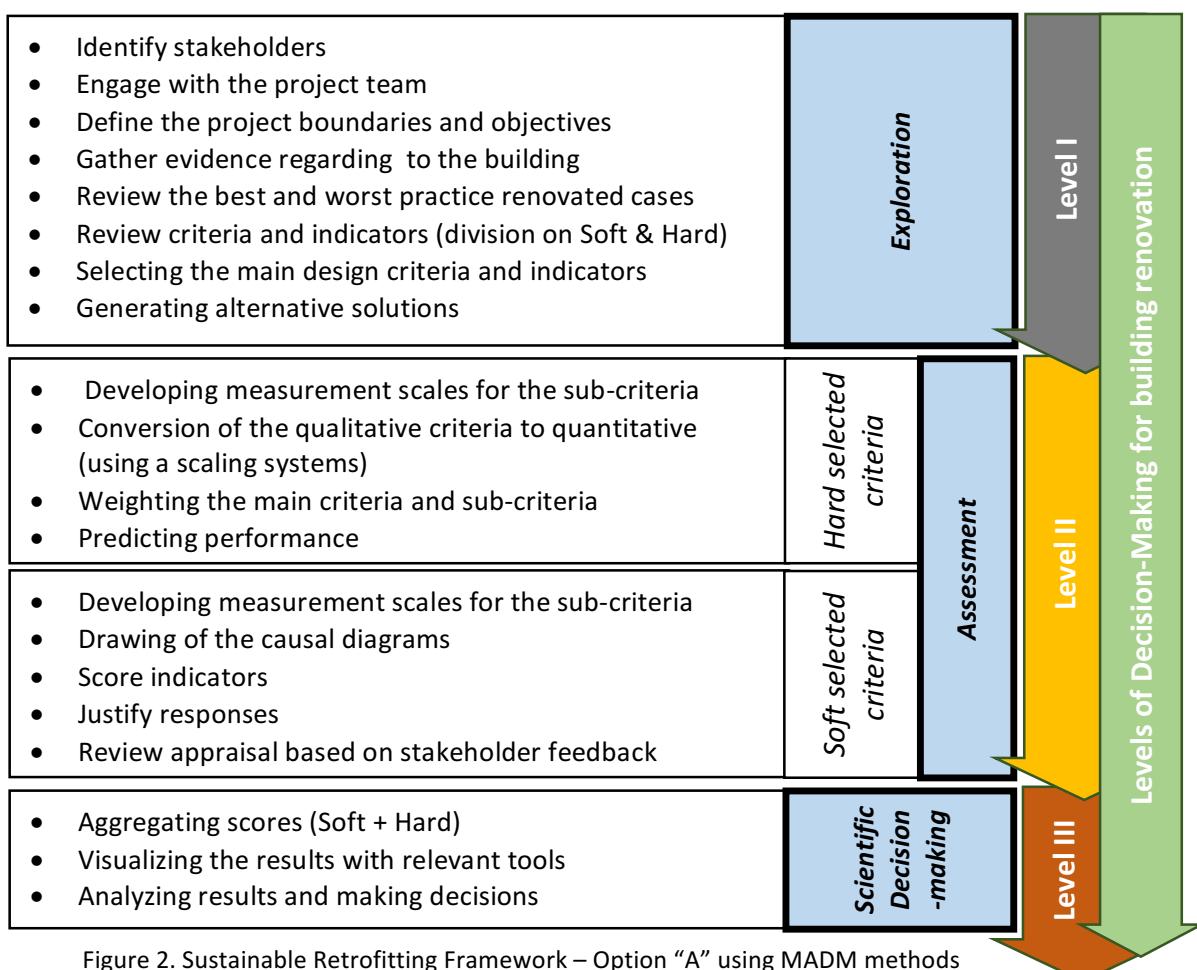


Figure 2. Sustainable Retrofitting Framework – Option “A” using MADM methods

Level I - The *Exploration* stage targets the identification and addressing the conditions and details regarding to the buildings and the stakeholders who are involved in the process. The decision that is made at the end of this level is often relevant for renovation of the detached and small buildings i.e., detached residential buildings. It is usually the case for experienced

consultant companies that their work scope specifically relates renovation of the similar types of buildings. It sounds logical since the buildings that located in a same region, have 1) similar functions (i.e. dwelling), 2) similar types including shapes and materials, as well as 3) customers with similar range of budgets, ultimately need to be renovated via application of the similar renovation scenarios. Renovation scenarios for these projects are generated while buildings are being explored. For this reason, there are methods such as the Danish - Total Value Model (Schunck, 2011) and/or RENO-EVALUE (Jensen and Maslesa, 2015) and/or STBA<sup>3</sup> (2012) that has been developed, specifically in order to finalize the decision for selection of the alternative renovations solutions at level 1, and can be applied for better decision-making.

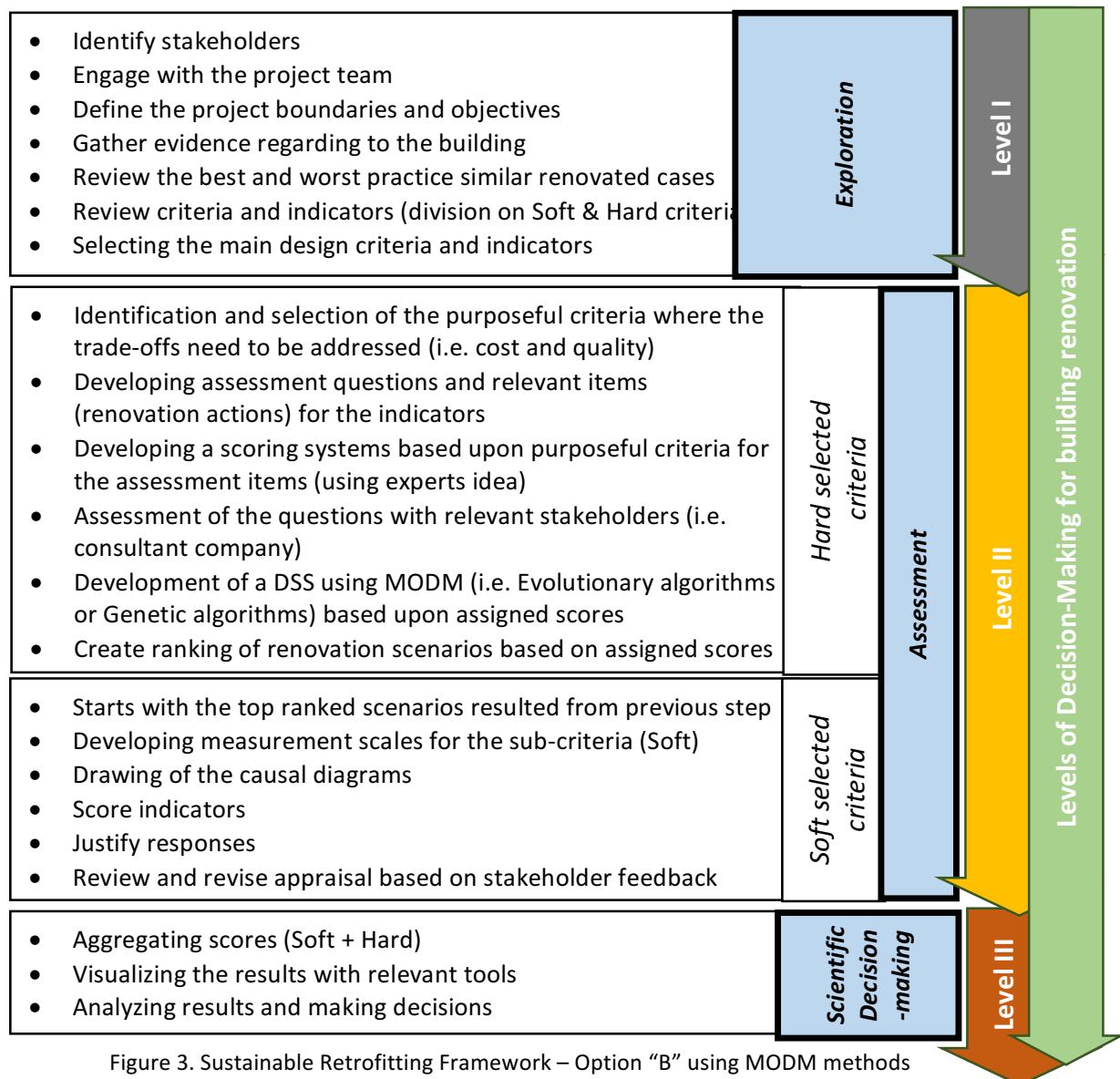


Figure 3. Sustainable Retrofitting Framework – Option “B” using MODM methods

**Level II** - Next, the Assessment stage intends to address the trade-offs or correlations between the sustainability criteria and renovation scenarios, using MCDM methods (Figure 1 - option “A” or “B”). The milestone here is about where the soft and hard (quantifiable) criteria have been separated early in the Exploration stage and subsequently can be assessed and

<sup>3</sup> <http://responsible-retrofit.org/wheel/>

addressed in Assessment level, scientifically. It is called “scientifically”, due to the terms defined as scientific design in (Cross, 2001). It should be underlined that the MCDM methods here are able to apply on hard/quantifiable criteria. Next, the soft criteria are addressed upon the outcomes of hard/quantifiable criteria regarding to either pre-designed renovation scenarios (option “A” – Figure 2) or generated ones using DSS (option “B” – Figure 3) and finally the decision is made using brainstorming between the stakeholders.

Level III - The major difference between level 2 and 3 is process of fully scientific decision-making. This level has been named Scientific Decision-makings since it is considered to aggregate and validate the scores regarding to the both hard and soft criteria using MADM methods.

Comparing the frameworks which have been developed in this section, for option “A” the scenarios are generated during the level 1 where a problem is being explored; in the contrary for option “B”, the scenarios are developed in level 2 (the *Assessment*) concentrating on addressing the trade-offs between criteria. It is worth noting that, the decision-making at level 3 using option “B” (Figure 3) is introduced as a fully scientific approach for building renovation. Therefore, following the description provided in section 1 (Introduction), the decision-making at level 3 of option “B” is referred in order to match the HMSR on Value Map.

## Conclusion and future research work

Looking at a project holistically for potential energy savings invariably means using an integrated design process. It is then developing a design process, which explores the interdependency between different building systems and renovation goals towards achieving sustained prosperity at the end of the day. This paper explored decision-making processes and frameworks in building renovation context, which identifies a need for introducing three different decision-making levels to help stakeholders in the renovation process to discuss their project “on the same level” and make transparent decisions in a rational order. As such, two frameworks were structured based on the two different MCDM methods including MADM and MODM. Each framework were divided through three levels consisting of the different activities. The decision-making at the third level was considered as a scientific design approach and is introduced as an integrated design process implementation and evaluation for the use of Value Map and in HMSR. Further regarding to the RE-VALUE project, the effort is the development of a scientific decision-making approach where a decision can be made at the third level of decision-making. Therefore, future studies will concern the development of a conceptual framework of a possible DSS concentrating on MODM and thus use of the second developed framework (option B) in the present paper.

## References

- Ascione, F., Bianco, N., Francesca De Masi, R., Mauro, G.M. and Vanoli, G.P. (2015). Design of the Building Envelope: A Novel Multi-Objective Approach for the Optimization of Energy Performance and Thermal Comfort. *Sustainability*, 7, pp. 10809-10836.
- Buildings Performance Institute Europe [BPIE] (2013). A guide to developing strategies for building energy renovation. Retrieved March 10, 2015, from [http://bpie.eu/documents/BPIE/Developing\\_Building\\_Renovation\\_Strategies.pdf](http://bpie.eu/documents/BPIE/Developing_Building_Renovation_Strategies.pdf)
- Burton, S. (2012). *The Handbook of Sustainable Refurbishment: Housing*. Abingdon: Earthscan.
- Checkland, P. (2000). Soft Systems Methodology: A Thirty Year Retrospective. *Systems Research and Behavioral Science*, 17, pp. 11-58.

- Climaco, J. (1997). *Multicriteria analysis*. New York: Springer
- Cross, N. (2001). Designerly Ways of Knowing: Design Discipline versus Design Science. *Design Issues*, 17(3), pp. 49-55.
- European Commission [EC] (2014). Energy-Efficiency Buildings, Energy Union and Climate. Retrieved December 11, 2015, from <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>
- Jensen, P.A. and Maslesa, E. (2015). Value based building renovation – A tool for decision making and evaluation. *Building and Environment*, 92, pp. 1-9.
- Jensen, S.R., Kamari, A., Strange, A. and Kirkegaard, P.H., (2016). Towards a holistic approach to retrofitting: A critical review of state-of-the-art evaluation methodologies for architectural transformation. In: WSBE 2017 (World Sustainable Built Environment) conference, Hong Kong, China. (accepted but not published yet)
- Juan, Y., Gaob, P. and Wangc, J. (2010). A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings*, 42(3), pp. 290–297.
- Kamari, A., Jensen, S.R., Corrao, R., and Kirkegaard, P.H., (2016a). Towards a holistic methodology in sustainable retrofitting: Theory, Implementation and Applications. In: WSBE 2017 (World Sustainable Built Environment) conference, Hong Kong, China. (accepted but not published yet)
- Kamari, A., Corrao, R., and Kirkegaard, P. H. (2016b). Sustainability focused Decision-making in Building Renovation. *International Journal of Sustainable Built Environment*, Manuscript submitted and is being reviewed for publication.
- Keeney, R. L. (1992). *Value-Focused Thinking*. Cambridge: Harvard University Press
- Lee, C.K, and Kim, S.K. (2007). GA-based algorithm for selecting optimal repair and rehabilitation methods for reinforced concrete (RC) bridge decks. *Automation in Construction*, 17(2), pp. 153-164.
- Likert, R. (1932). A technique measurement of attitudes. *Archives of Psychology*, 22, pp. 5-55.
- Pareto, V. (1896). *Cours d'Economie Politique*. Geneva: Droz.
- Petkov, D., Petkova, O., Andrew, T., and Nepal, T. (2007). Mixing Multiple Criteria Decision Making with soft systems thinking techniques for decision support in complex situations. *Decision Support Systems*, 43, pp. 1615–1629.
- Saaty, T.L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. New York: McGraw-Hill.
- Schunck, C. (2011). Totalværdimodellen – Energirenovering med merværdi. Retrieved September 20, 2015, from [http://www.plan-c.dk/\\_files/Dokumenter/rapport/totalvrdimodellen\\_14juni2011.pdf](http://www.plan-c.dk/_files/Dokumenter/rapport/totalvrdimodellen_14juni2011.pdf)
- Taha, R.A. and Daim, T. (2013). Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review. in Daim et al (Ed.), *Research and Technology Management in the Electricity Industry*. Part of the series Green Energy and Technology, Springer, New York, pp. 17-30.
- Triantaphyllou, E., Shu, B., Nieto, S.S. and Ray, T. (1998). Multi-Criteria Decision Making: An Operations Research Approach. *Encyclopedia of Electrical and Electronics Engineering*, 15, pp. 175-186.
- Volvačiovas, R., Turskis, Z., Aviča, D. and Mikšienė, R. (2013). Multi-attribute Selection of Public Buildings Retrofits Strategy. *Procedia Engineering*, 57, 1236 – 1241
- Wang, J., Jing, Y., Zhang, C., and Zhao, J. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, 13(9), pp. 2263-78.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Campus Audit Squads for Energy (CASE): understanding behavioural patterns and energy use of plug loads

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**Abstract:** Awareness about energy use related to plug loads is increasing. Previous studies showed that plug loads comprise 20 to 35% of electricity consumption in office buildings (Hafer, 2015; Moorfield, 2011; Sanchez, 2006). This study examines plug load use in a department office on a university campus. The goal is to identify behaviours and operating patterns of plug load energy consumption. An equipment inventory was developed which categorized equipment by type and location. The study took place over a one-month period, using Onset Hobo UX18-120 plug load data-loggers, which recorded the energy used by all devices in the office. The devices were connected to plug strips and then to data-loggers in 8 work spaces. The categories of device-use included: 1) Task (computers, printers, scanners, chargers), 2) Thermal Comfort (fans, a/c), 3) Lighting (desk/standing lamps), 4) Miscellaneous (refrigerator, coffeemaker, microwave, toaster, water cooler). The Task and Thermal Comfort categories accounted for more than 60% of the plug load use consumption for the month. Energy usage per square foot [square meter] was calculated to help understand energy performance within the spaces. Surprisingly, phantom loads accounted for 29% of the total plug loads for a month period.

**Keywords:** Plug load, Phantom load, energy use intensity, and behavioural pattern

### Introduction

With the increasing awareness of energy consumption, many efforts have been directed not only at finding renewable energy sources but also the making more energy efficient and environmentally conscious product. Lighting, refrigeration and heating products take the leading spot in term of energy saving innovation through the effort of many energy efficiency programs such as Energy Star. The US Energy Information Administration reported that increase efficiency in lighting and heating/cooling equipment account for a projected 0.7% annual decrease of delivered energy in their annual energy outlook report. On the other hand, the report also takes note of expected 21.4% increase of Energy Use Intensity (EUI) for different electric load due to the lack of a federal standard. These fact accounts for the reverse in the percentage, plug load slowly becoming the dominant factor in a building operational energy consumption.

The importance of plug loads in energy consumption in commercial and office buildings is more visible every day, as technology advances more devices becomes available for usage. Previous studies have documented equipment and other miscellaneous plug loads inventories, which can be attributed to consuming between 20 to 35% of electricity for office buildings (Hafer et al., 2015, Moorefield et al., 2011; Sanchez, et al., 2006). But limited studies

have addressed equipment profiles of energy usage (Moorefield et al., 2011), and none regarding user behaviour. This particular study focused on behaviour and operating patterns to identified how it affects plug load energy consumption for a particular office working environment.

## Methodology

The present study was carried out through fieldwork measurements of energy used for different appliances in the Architecture and Interior Architecture Department office. Onset Hobo UX18-120 Plug Load dataloggers were utilized as the main equipment, in which devices were physically grouped and connected with plug strips to the data-loggers in 8 working spaces. The appliances were organized into four main categories base on their usage, which included: (1) Task, (2) Thermal Comfort, (3) Lighting Comfort (4) Miscellaneous, as shown in Table 1.

For each of the working space, data was collected during 24-hour basis for a monitoring period of four-week over the summer season (mid-June to mid-July, 2016). This included normal occupancy hours during the weekdays (Monday through Friday) from 8:00 to 4:00 pm, with small to none occupancy over the weekends (due, to summer sessions occupancy over the weekends was very minimal).

Also, Plug Load Intensity (PLI) index was measured, which in this study is defined as the fraction of plug load use (kWh) [BTU] by the area of the office ( $m^2$ ) [ $ft^2$ ].

This study also determined Phantom Load index, which is defined as the consumption of energy while devices are turn off but still plugged into an outlet, through the study of energy use profiles by looking at individual equipment categories. An average range trend (x-value) was estimated for an active load (during use) and one for un-active or phantom load (during no use). From the range values selected it was determined the following: “> x-value = active load”, “< x-value = phantom load.” Phantom loads from all device categories were added to determine a total phantom load index for each space type.

Table 1. Appliances organized into four categories.

APPLIANCES	
Task	<i>Computer, computer screen, printer, label maker, landline, speaker</i>
Thermal comfort	<i>Heater, fan, Air conditioner</i>
Lighting comfort	<i>Desk lamp, standing lamp</i>
Miscellaneous	<i>Coffee maker, refrigerator, microwave, water cooler</i>

		Task	Lighting Comfort
		Thermal Comfort	Miscellaneous
1	Plug Strip 1	iMac	
	Plug Strip 2	LaCie Storage Device	
	Plug Strip 3	Mini Mac	
2	Plug Strip 4	Dell Screen	
	Plug Strip 5	Holmes Tower Fan	
3	Printer HP LaserJet 940DN	Holmes Space Heater	
4	Plug Strip 6	LaCie Oscillating Fan	
	Plug Strip 7	Tilt Air Conditioner	
5	Plug Strip 8	Fridge	
	Plug Strip 9	Espresso Maker	
6	Plug Strip 10	Dell Screen 1	
	Plug Strip 11	Dell Screen 2	
7	Plug Strip 12	HP LaserJet 1320n	
	Plug Strip 13	LaCie Storage Drive	
8	Plug Strip 14	MacBook Pro	
	Plug Strip 15	Standing Lamp	
9	Plug Strip 16	Desk Lamp	
	Plug Strip 17	Tilt Air Conditioner	
10	Plug Strip 18	Holmes Tower Fan	
	Plug Strip 19	MacBook Pro	
11	Plug Strip 20	Toaster	
		Microwave	
12		Refrigerator	
		Coffee Maker	
13		Water Cooler	
		TV	
14		Sound System	
15		Holmes HT17 Tower fan	

Figure 1. Floor plan of Architecture and Interior Architecture Department Office with appliances inventory identified by categories.

## ***Office Context***

The Architecture and Interior Architecture Department Office provided an interesting study scenario to analyse office behaviours and how operating patterns of use affect plug load energy consumption. Within the office; various program and patterns of usages are present, different space characteristic (i.e. access to daylighting and natural ventilation for some office spaces in contrast to others that do not) and an array of appliance devices are present at each working area or storage room with mini kitchen, provided a unique study environment. The used of different data loggers allowed to measure the various use within each of the areas inside the department office, as well as helping determined user's behaviours. During the assessment, the following spaces that were available to measure energy consumption during the monitoring period were: Front Office, Office 1-5 (admissions, counselling, office assistant, assistant to the head, department head), Meeting Room and Storage Room as seen in Figure 1. To register the different appliance available and used at each office space an equipment inventory was produced as seen in Figure 1. This help organized the devices into four categories previously mentioned.

## **Results**

### ***Overall Office Analysis***

From the entire plug loads measurements obtained during one month, the total energy use within the four main categories, task related appliances contributed the most, at 41% of the total use, in Architecture and Interior Architecture Department Office. Thermal and miscellaneous devices included 28% and 23%, while lighting appliances only accounted for 8% of the total energy, as seen in Figure 2. The high percentage of energy use for the thermal appliances can be attributed to the use of cooling equipment during operational hours over summer season (i.e. fan and air conditioners) which were present at front office as well as office 1, 3, and 5. Therefore, energy use within the different spaces differs depending on the type of equipment in the space, and pattern of usage of the room type. Consequently, it is important to analyse plug loads by space type within the four categories, to have a better understanding of the energy usage distribution during that month, as shown in Figure 3. Front office accounts for the most energy use with a total of 77.64 kWh [264,918.66 BTU] for the entire month, followed by Office 1 with a total of 48.15 kWh [164,294.61 BTU]. Office 4 and 5 on the other hand, presented the lowest amounts energy use for that period, with a total of 8.80 kWh [30,026.84 BTU] and 5.51 kWh [18,800.89 BTU] respectively.

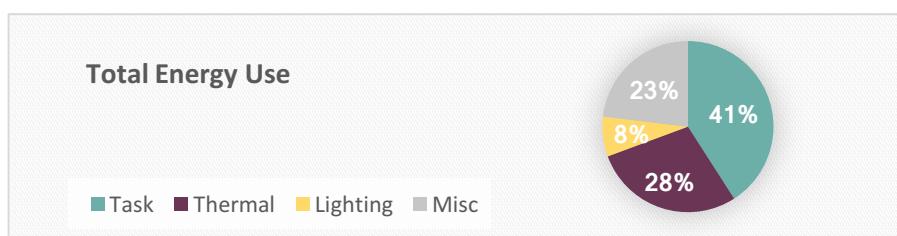


Figure 2. Total energy use by appliance groups during a month period.

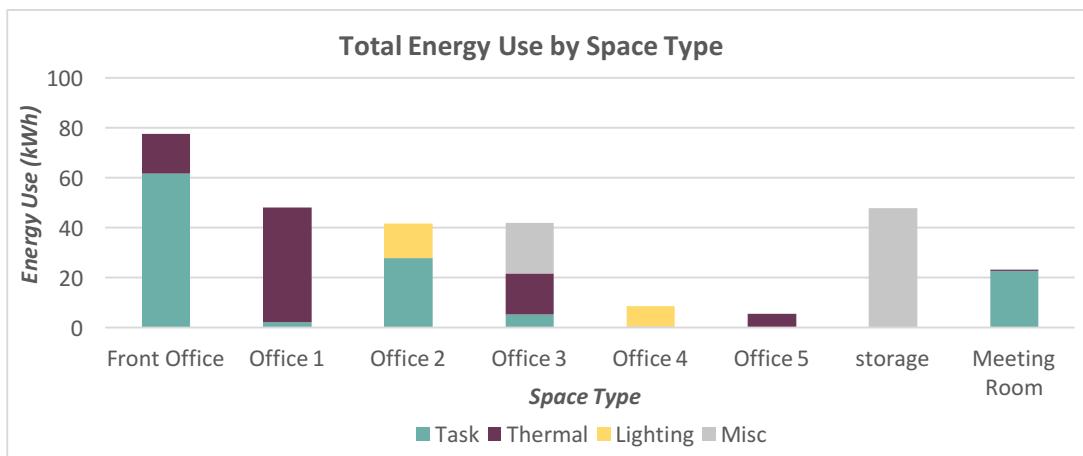


Figure 3. Total energy use by appliance groups during a month period.

While the front office has the highest energy usage from the entire Department Office, if we look at PLI index (i.e. kWh/m<sup>2</sup>), Office 3 has the highest value followed by Office 2, in comparison to other office spaces which have a similar surface area, Figure 4. If we compare all the office spaces, the storage room has the greatest PLI index with over 0.09 kWh/m<sup>2</sup> [307.09BTU/ft<sup>2</sup>]. Inversely, the front office is the least intense in terms on PLI because of its double programmatic uses, reception as well as a circulation area as the primary pattern of use, Figure 4.

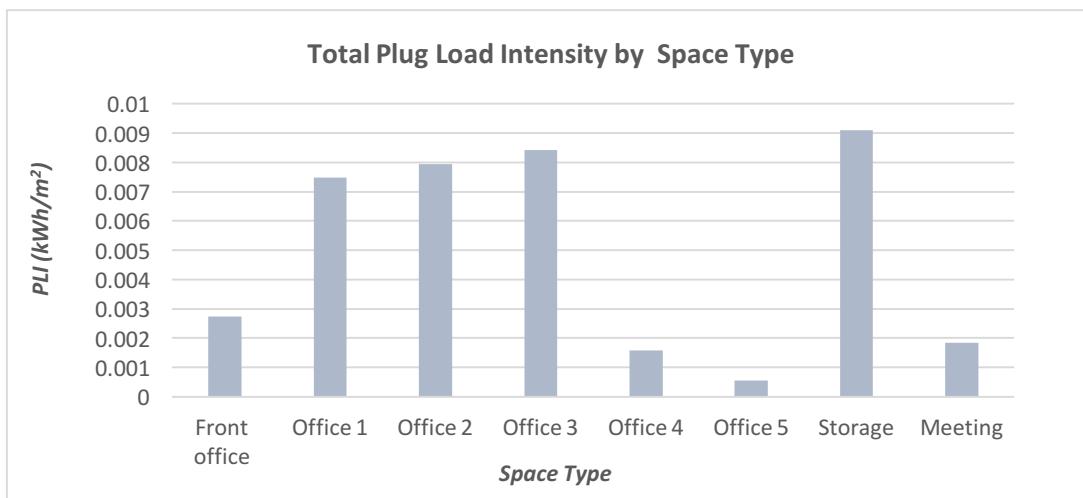


Figure 4. Plug Load Intensity (PLI) by space, office 3 has the biggest PLI index and the storage room.

Regarding phantom loads, the meeting room has the highest relationship between phantom load value of 20.05 kWh [68,413.43 BTU] versus an active load value of 3.22 kWh [10 987.09 BTU], most probably caused by miscellaneous conference equipment that is continually plugged into the outlet, while devices are not in use. For office spaces, front office registered the highest phantom load value, 14.88 kWh [50,772.66 BTU], follow by office 2, 7.97 kWh [27,194.76 BTU], as seen in Figure 5.

To understand behaviour and energy use across the month, we now looked at the total energy consumption across the four categories for the entire office by each week. As evidenced in Figure 6, the highest energy use pattern occurs during the second week of the month for plug loads measurements. During that week, measures reached up to 89.85 kWh

[306580.92 BTU], while for other weeks' energy use ranged between 62.00 kWh [211552.78 BTU] to 80.00 kWh [272971.33 BTU].

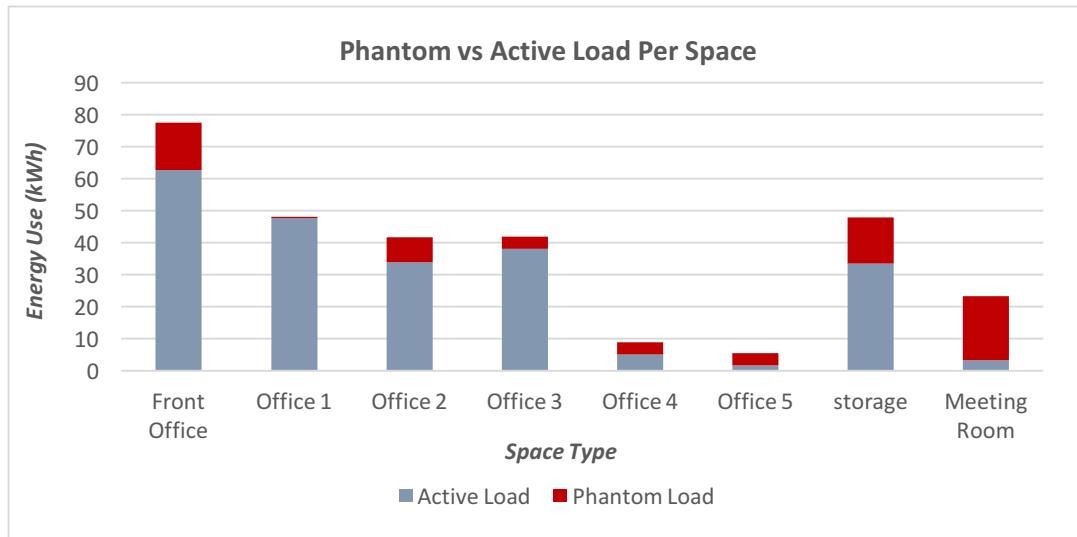


Figure 5. Phantom vs. active load. Meeting room had the biggest phantom load relationship to active load, due to the miscellaneous conference equipment that is continually plugged while not in use.

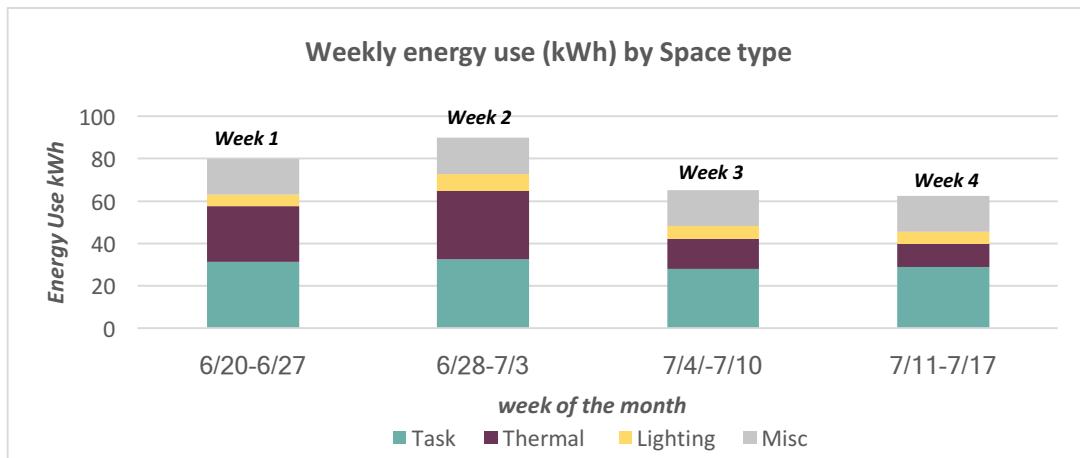


Figure 6. Energy use distribution by type per week.

### **Energy Use Study of One week**

The plug loads of the entire month revealed an unusual increase of energy on Monday to Tuesday morning during week two, reaching a peak of 0.25 kWh [853.03 BTU] much higher than the average of 0.04 kWh [136.48 BTU], as seen in Figure 7. This phenomenon can probably explain the increment of energy use during week two, shown in Figure 6. During the four-week period, energy consumption ranged on average a high of 0.15 kWh [511.82 BTU] and a low of 0.02 kWh [68.24 BTU] depending on equipment and pattern usage. Energy use values only reached zero in a couple of occasions over the month, due to a power outage.

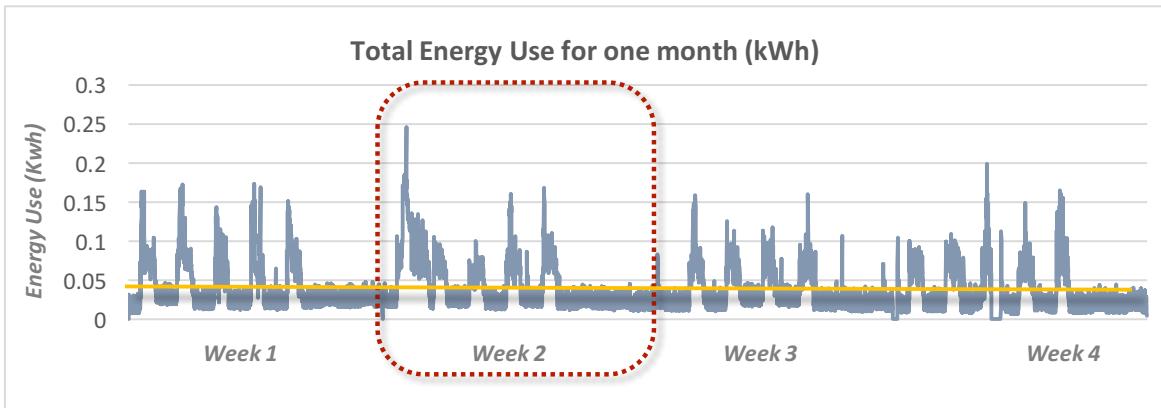


Figure 7. Total energy use per week, case study (week 2) Monday June 27<sup>th</sup> through Sunday July 3<sup>rd</sup>, 2016.

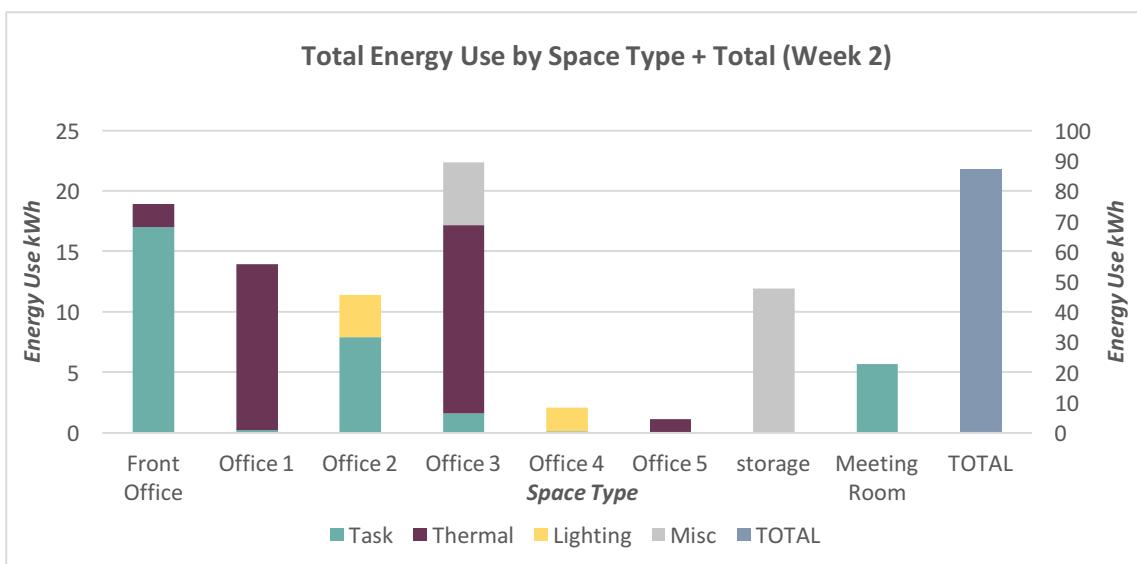


Figure 8. Energy use by office in week 2 case study: June 27<sup>th</sup> through Sunday July 3<sup>rd</sup>, 2016.

Plug loads analysis per week shows a slight increase of energy use in office 2, 11.38 kWh [38830.17 BTU] (representing 27.22% of the total energy consumption for that month). In the other hand, a significant increase for office 3, 22.37 kWh [76329.60 BTU] (representing 53.40% of total energy use of that month) during week two, in comparison to the rest of spaces for the whole month, as seen in Figure 8. For this reason, we chose to delve deeper into the energy use behavior patterns for Office 2 and 3.

For Office 2 and 3, as seen in Figure 9 and 10 plug load profiles, shows a typical weekday use (during operational hours) while no use, depending on equipment type, during night time and the weekends in which plug loads reached zero values. Task equipment in Office 3 shows an unusually large amount of phantom load while task devices in Office 2 demonstrate that it reached zero kWh when not active. In Office 2, task and lighting were the main categories of appliances present in the space. In particularly, three lamps accounted for primary lighting energy use of plug loads contributor (through the constant and regular state), including the weekend hours as devices were placed on a timer system. Data logger measuring a refrigerator in office 3, shows the refrigerator's typical oscillating energy totaling 20.22 kWh [68993.50 BTU] for the month. This refrigerator alone represented 42% of total energy use from all other appliances in the storage room space combine. In Figure 10, Office 3 reveals a

sudden intensive use of the air conditioner on Monday, which seems to be left active through the night to the next morning. The explanation of this could have been due to raised outside temperatures registered over that weekend, reaching a maximum of 31°C [88°F] on Saturday, 27°C [81°F] on Sunday and 26°C [79°F] on Monday. In office 2, task equipment graph as seen in Figure 9, during Monday and Wednesday it shows that the computer was not shut down completely in which occasional spikes are evidenced outside the office hours. This could have happened due to software updates or user leaving the computer on. During week two, the total active plug loads from all office spaces summed a total of 72.56 kWh [247584.99 BTU]. From the actives load's total, leaves a difference of 16.95 kWh [57835.80 BTU] of plug loads, which is associated phantom loads for that week (representing 18% of the total energy use), that in week 2 was 89.85 kWh [306580.92 BTU] as seen in Figure 8.

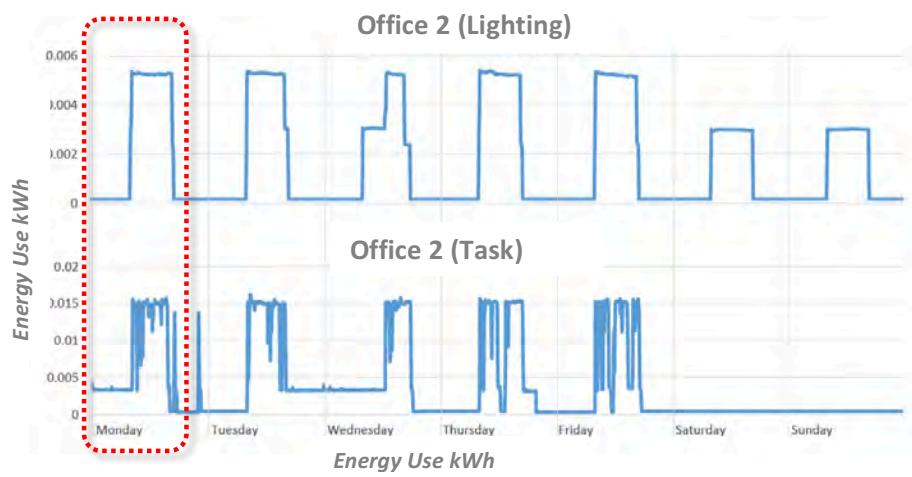


Figure 9. Office 2 energy use in week 2 case study: June 27<sup>th</sup> through Sunday July 3<sup>rd</sup>, 2016

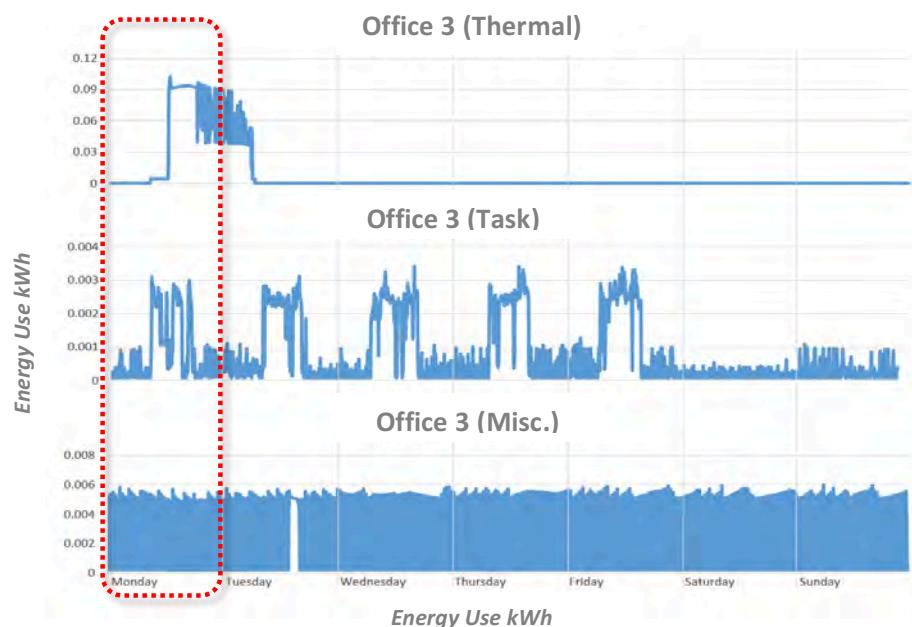


Figure 10. Office 3 energy use in week 2 case study: June 27<sup>th</sup> through Sunday July 3<sup>rd</sup>, 2016.

Further analysis dug deeper into specific days (for a 24-hour period) of week 2, but due to the length limitation of this paper, not all that information can be confined in this section but found the results from Office 3 to be important to mentioned. Office 3, in a 24 hours'

analysis showed a continuously used of an air conditioner from noon on Monday until 8:00 am the next morning. The energy use of the air conditioner peaked at 0.10 kWh [341.21 BTU] and averaged around 0.07 kWh [238.84 BTU] during that day, a much higher average use than any other equipment in the entire department office. Even though this happened only once in the whole month, it contributed to 20% of the Thermal Energy consumption of the office and 5% of the total plug load use for the entire month.

## Conclusion

Selection of equipment and human behaviour can have tremendous impacts on energy use, particularly in the office environment. We found that just one appliance can impact total energy use by something as simple as leaving it running longer than is needed. Also, newer more energy efficient appliances, in this case, an Energy Star refrigerator used less energy than many of the office appliances used together.

Analysing plug loads over an entire month period, allowed us to identify operating patterns of plug loads by week and weekend, in specific office spaces, and by device category.. We could delve deeper into understanding of user behaviour and equipment categories, as relevant variables that affect energy consumption, which in traditional studies of energy use this usually doesn't get identified. For example, the total energy use of office 3, could have been significantly reduced with the choice of more efficient equipment and user habits, compared to other working spaces in the case study. This study serves as the basis to develop future research, such as, how patterns of use can change over a year due to seasonal changes, as well as, indoor interior conditions. By looking at plug loads energy consumption profiles, can help raise awareness of the importance and impact of this variable can have when addressing energy efficiency in office, commercial as well as other building typologies.

## Acknowledgement

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## References

- Hafer, M. et al., 2015. Inventorying Plug Load Equipment and Assessing Plug Load Reduction Solutions on a University Campus.
- Moorefield, L., B. Frazer and P. Bendt, Ph.D. 2011. Office Plug Load Field Monitoring Report. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC- 500-2011-010.
- Sanchez, M. et al., 2006. Space Heaters, Computers, Cell Phone Chargers: How Plugged In Are Commercial Buildings? *ACEEE Summer Study on Energy Efficiency in Buildings*, pp.304–315.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Assessment of thermal comfort and passive design strategies in Millennium Schools in Ecuador

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**Abstract:** The Ecuadorian government embarked on the Millennium Schools programme (UEM) to benefit the poorest areas of the country, providing them free access to education. The program is underpinned by intentions to promote healthier educational environments. Disregarding the three variations of climatic regions in the country, prototype designs are adopted for the ease of using off-site prefabricated elements, optimizing construction time, and lowering costs. This study uses subjective surveys to determine the desired conditions in classrooms before implementing passive strategies; and, aims to increase thermal comfort hours while decreasing energy consumption. The surveys interestingly show that perceptions of thermal comfort differ from published standards and can be influenced by other perceptions regarding the space quality. Two UEMs located in Babahoyo and Quito, Coast and Andean region respectively, were selected for conducting the surveys and monitoring indoor conditions to validate a simulation model. Building dynamic simulation modelling is used to test the thermal performance and the efficiency of architectural passive strategies. The prototype buildings are capable of maintaining thermal comfort conditions on an average 70% in Quito, and 64% in Babahoyo of occupancy hours respectively. Using optimum architectural parameters, thermal comfort can increase to 95% in Quito and 80% in Babahoyo.

**Keywords:** Thermal comfort, Passive strategies, Educational Buildings, Climate responsive, Adaptive comfort

### Introduction

The Ecuadorian government, over the last eight years, has embarked on the construction and refurbishment of school buildings to promote healthier educational environments. Prototype designs are adopted for the ease of using off-site prefabricated elements, optimizing construction times, limiting material waste and lowering construction costs and human workforce (Ministerio de Educación, 2014). Millennium Schools programme (UEM) is based on the construction of prototype school buildings to provide free access to education throughout the country.

The UEM programme started in 2008 on the conceptual idea to reallocate students of small schools into an infrastructure that houses all the levels of education and has all the necessary facilities. The UEM design was replicated all over the country without further considerations to the local climate or people adaptations and expectations.

Ecuador has three natural regions with different climatic conditions. The Coast and Amazon regions have an average temperature of 25°C and humidity of 90%. The Andean region average temperature is 16°C and humidity of 75% (Cedeño & Donoso, 2010). UEM's design for the temperate climate does not include any active system to regulate indoor conditions; in warm climates the design incorporates ceiling fans. Thermal comfort has been defined as "the state of mind that expresses satisfaction with the surrounding environment" (ASHRAE, 2013). This definition highlights the social and psychological dimensions involved as

well as the physical parameters. Thermal comfort in classrooms needs to be assessed carefully due to the high occupant density, the impact of discomfort on learning performance and the limited opportunity for children to adapt to the indoor conditions. Humphreys (Humphreys, 1977) concluded children are less sensitive to temperature changes than adults.

Thermal comfort studies in classrooms have been conducted under two methodologies: objective surveys (PMV/PPD) and subjective surveys based on thermal sensation votes (TSV) and thermal preference votes (TPV). Using subjective surveys the neutral temperature in classrooms has been found to be 4°C lower than the prediction using the PMV/PPD model and 2°C lower than the adaptive model equations. (Zomorodian, et al., 2016)

Since 900 UEM schools are still in planning stage it is necessary to evaluate student's expectations of the indoor environment. Furthermore, as current standards neglect the use of passive architectural strategies, there is a need to evaluate the thermal performance of the buildings and the possibility of improvement based on architectural parameters. Not many studies have been made on the influence of passive strategies over indoor comfort conditions based on thermal requirements of students (Zomorodian, et al., 2016) (Zahiri, et al., 2016). These studies use subjective surveys to determine the desired conditions before implementing passive strategies; and, aim to increase thermal comfort hours rather than to diminish energy consumption.

The objectives of this study are as follow:

- To investigate student's perception of thermal comfort in classrooms, their acceptability and preferences using subjective surveys
- To determine the boundaries for comfortable thermal sensations, the neutral and preferred temperatures.
- To test the efficiency of architectural passive strategies for improving indoor thermal comfort in classrooms.

## Methodology

Two UEMs located in Babahoyo and Quito, Coast and Andean region respectively, were selected for conducting the surveys and monitoring indoor conditions to validate a simulation model. Building dynamic simulation modelling is used to test the thermal performance and the efficiency of architectural passive strategies. The UEM in Quito houses 2280 students, while the one in Babahoyo houses 2086. Figure 1 displays the site plan for both schools.

The design is based on a modular grid classroom that can be replicated and extended to house the different facilities required. The modular classroom serves 35 students with an area of 1.63 m<sup>2</sup> per student (Ministerio de Educación, 2014). The 12-classroom block houses classrooms distributed on two-stories around a central covered courtyard. The modular windows allow natural cross ventilation with a window to wall ratio (WWR) of 34% in external façade and 15% in the internal. The building has an S/V of 0.27 and an infiltration rate of 5.7 air exchanges per hour (CITEC UBB, 2011).

Figure 2 shows the classroom configuration with the position of the monitoring equipment and the school floorplan showing the surveyed classrooms.

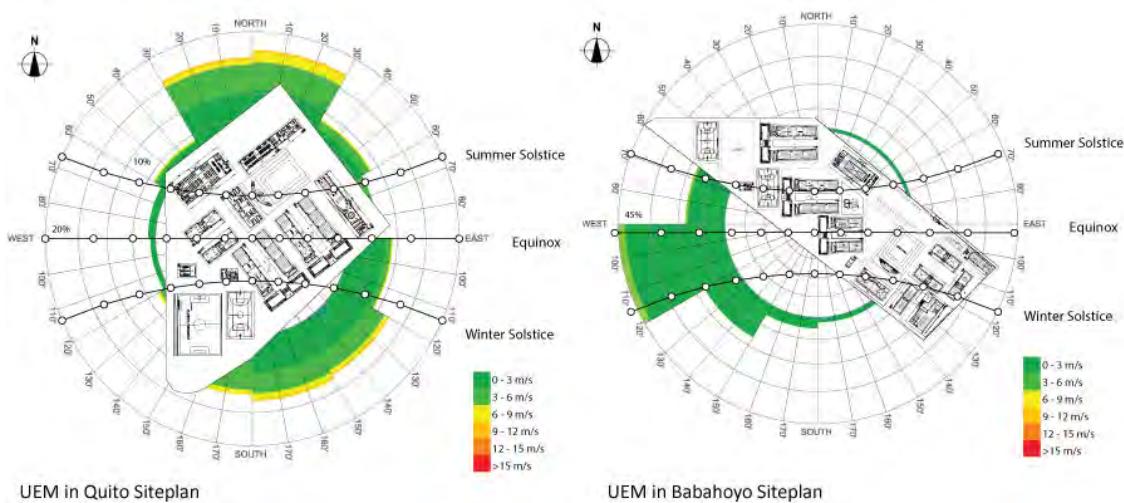


Figure 1. Siteplans of both UEMs with environmental parameters

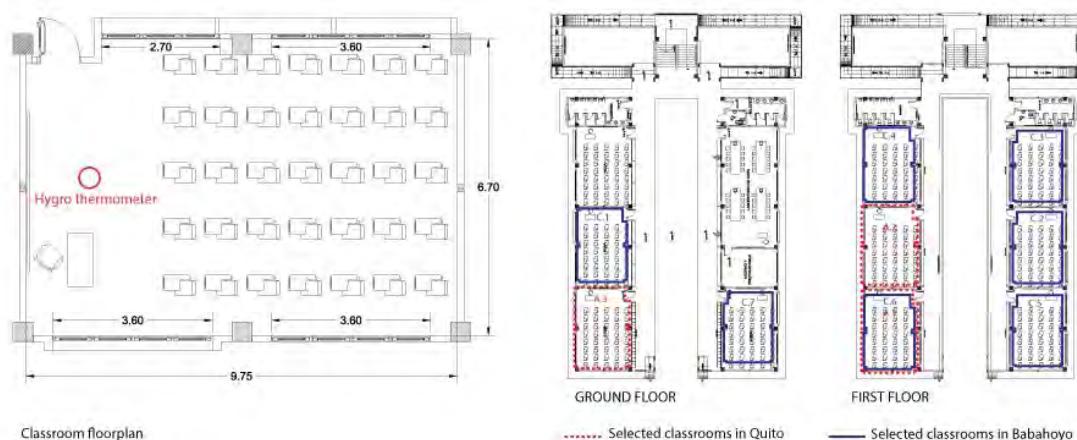


Figure 2. Classroom design and school floorplan

### **Field measurements**

The sample size for Quito was of 83 people, conducted in three classrooms on the 21st of June. A larger sample size was collected for Babahoyo involving 210 subjects. The surveys were done on the 22nd of June and 6th of July in four and three classrooms respectively.

The subjective questionnaire consisted of 10 questions divided into three parts. The first section collected demographic information and the second section referred to thermal perception and preferences. For thermal sensation, two 7-point scales were used (ASHRAE and Bedford), the 3-point McIntyre scale served to determine the thermal preference. Acceptability was assessed through direct votes and the overall satisfaction with the environment was measured on a 7-point scale. The third section related to students concentration and sleepiness.

### **Data Analysis**

The classrooms' indoor conditions were evaluated against two methods: (1) the PMV/PPD method in ASHRAE 55 and (2) the Adaptive method in EN-15251. The PMV/PPD determines the mean value for the thermal sensation votes (MTSV) of a group of people, which can range between -3 (cold) and +3 (hot) on the 7-point thermal scales. The adaptive method relies on the mean outdoor temperature to establish thermal comfort charts. The indoor conditions

were contrasted against student's responses in order to establish the actual thermal comfort ranges, neutral and preferred temperatures.

The prototype model for the UEM was created in IES Virtual Environment Software and were validated according to ASHRAE Guide 14 using two indexes of error the MBE and cv(RMSE). The model calibration for Quito gave an MBE value of +3% and a cv(RMSE) of 7.2% while for Babahoyo the MBE is +2%, and the cv(RMSE) is 4.5%.

### **Thermal comfort in classrooms in UEMs:**

#### ***PMV/PPD in ASHRAE 55***

This method predicts the thermal sensation of a group of people based on six input values: air temperature, mean radiant temperature, relative humidity, air velocity, clothing level and metabolic rate. Air temperature and relative humidity were measured in each classroom, the clothing levels were determined using tables in ASHRAE 55, and the metabolic rate was taken from the research conducted by Teli, et al (2014).

Table 1 displays the results for Quito and Babahoyo. The PMV in the city of Quito is -0.58 (slightly cool) and the PPD is 13.6% which is slightly outside the comfort limits (10% dissatisfaction). In Babahoyo the PMV and PPD are +2.04 (warm) and 72.7%

Table 1. PMV/PPD Analysis

UEM Quito						UEM Babahoyo					
Clas	°C	Hum	MTSV	PMV	PPD	Class	°C	Hum	MTSV	PMV	PPD
A.1	17.3	68.0	-1.0	-0.8	18.0	C.5	28.4	77	-0.2	1.5	49.0
A.2	17.7	61.0	-0.7	-0.7	17.0	C.6	28.8	74	0.0	1.4	47.0
A.3	20.3	51.0	-0.4	-0.2	6.0	C.7	29.8	74	0.7	1.8	68.0
<b>Mean:</b>			<b>-0.7</b>	<b>-0.6</b>	<b>13.7</b>	C.1	30.0	73	0.4	1.7	61.0
<b>Met:</b>				1.2		C.4	32.5	57	0.6	2.6	94.0
<b>Clo:</b>				0.9		C.2	33.0	53	0.9	2.5	91.0
<b>Mean Out Temp:</b>				15.9		C.3	34.5	51	1.0	2.9	99.0
						<b>Mean:</b>			<b>0.5</b>	<b>2.0</b>	<b>72.7</b>
						<b>Met:</b>			1.2	<b>Clo:</b>	0.6
						<b>Mean Out Temp:</b>			26.3		

#### ***Adaptive method in EN-15251***

The adaptive comfort was calculated using CBE tool to generate adaptive charts in compliance with EN-15251 Standard. Figure 3 shows the adaptive comfort range for both cities. The comfort zone is defined between 22 and 26°C for Quito and 25.5 and 30.3°C for Babahoyo. The measured temperatures were plotted against the adaptive charts for each region. In Quito the inside temperature is always below limits indicating occupants always feel cold, while in Babahoyo the indoor conditions are within comfort limits during morning hours.

#### ***Thermal sensation votes***

Figure 4 shows the TSV distribution in each classroom; the bold lines represent the average vote, the boxes the range of the majority of votes, and the vertical lines the total range of votes.

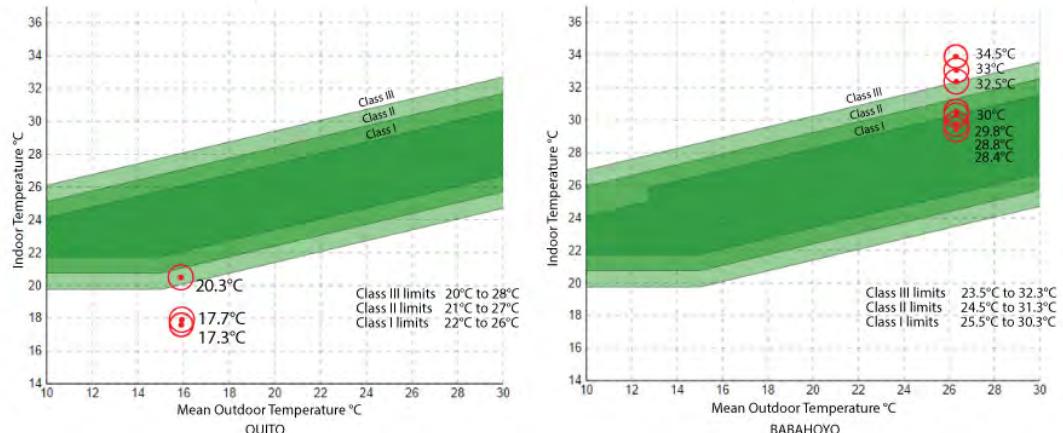


Figure 4. Adaptive Comfort charts for both UEMs

The MTSVs for Quito were -1.28 (cold) in ASHRAE scale and -0.63 (comfortably cold) in Bedford scale, showing that people voting on cold thermal sensations still evaluated them as comfortable. For Babahoyo the values were 0.67 (slightly warm) and 0.44 (comfortably warm), reflecting that people voting on warm thermal sensations evaluated them as less severe in Bedford scale.

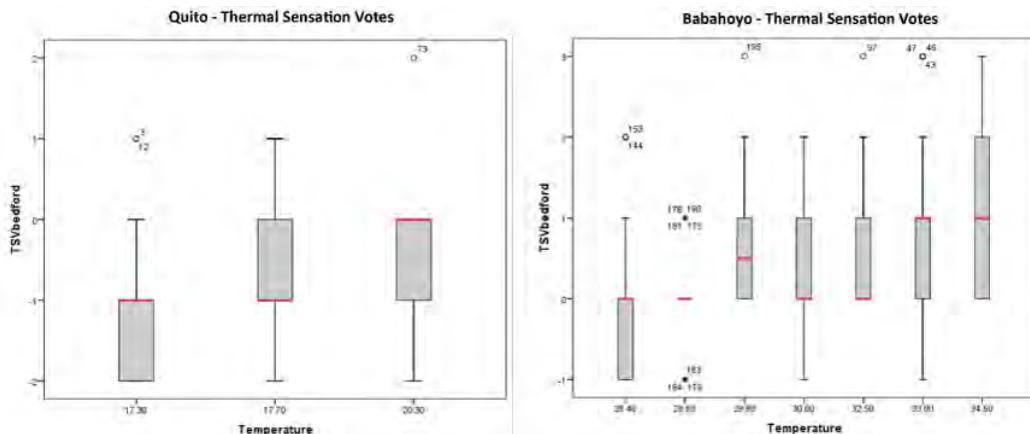


Figure 3. Thermal sensation votes for both UEMs

#### **Neutral temperature and thermal comfort range:**

Neutral temperatures were calculated using linear regressions of the MTSV against indoor temperatures. An ONEWAY ANOVA with Turkey-b test were used to analyse if the data had a significant variance between the MTSV that could be attributed to temperature.

The equations relating TSV and temperature are:

$$MTSV = 0.1626Ta - 3.7032$$

Equation 1 – Linear regression TSV Bedford Quito

$$MTSV = 0.1626Ta - 4.5496$$

Equation 2 - Linear regression TSV Bedford in Babahoyo

The neutral temperatures are those at which the MTSV is equal to zero. Using Equations 1 and 2 the neutral temperature are 22.30°C and 27.9°C respectively. Since for Quito, only three classrooms were involved, the comfort range was calculated using equation (1) to determine the temperatures at which the MTSV were +0.5 (90% acceptability). The comfort range for Quito is 19.7°C to 25.8°C. In Babahoyo it was calculated using a fitted quadratic equation between the percentage of acceptability and the indoor temperature. The intersections between the quadratic regression and the 90% acceptability axes gave a comfort range of 25.4°C to 32.2°C.

### **Preferred temperature**

Zomorodian (Zomorodian, et al., 2016) found that the preferred temperature differs from the neutral on an average 1.5 to 4°C. To obtain the preferred temperature two probit regression lines were used relating the people voting for warmer sensations against the people voting for colder sensations. Figure 5 shows the probit regression analysis for Quito and Babahoyo.

In Quito, the preferred temperature is 22.7°C, equal to the neutral temperature; in Babahoyo the preferred temperature is 3.5°C lower than the neutral one showing students favour colder temperatures. Thermal sensation and preferences differ since in Quito, 65.8% of the students in thermal comfort voted for warmer temperatures and in Babahoyo 59.23% voted for cooler temperatures.

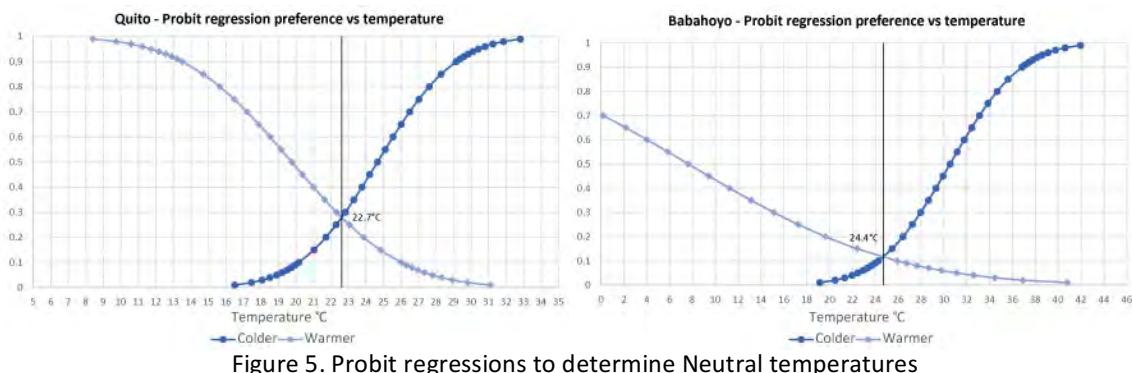


Figure 5. Probit regressions to determine Neutral temperatures

### **Thermal performance and the efficiency of architectural passive strategies**

The current school infrastructure in Quito has 70.6% of occupancy hours within comfort (19.7-25.8°C); while in Babahoyo, including the influence of ceiling fans, it has 67.8% of hours in comfort (25.4-32.2°C); by removing the fans, the percentage of hours in comfort drops to 63.8%. Zomorodian (Zomorodian & Nasrollahi, 2013) determined that the main architectural parameters influencing thermal performance are: infiltration rate, window to wall ratio, and orientation.

#### ***Infiltration rate***

In Quito infiltration is the major cause of coldness, by increasing the air tightness of the fabric to 0.5ach the percentage of hours in thermal comfort increases to 94.1%. Similar results were obtained in schools in Iran (Zomorodian & Nasrollahi, 2013) and Chile (Trebilcock, 2014).

In warm climates, a higher ventilation rate will result in greater heat transfer from the inside to the outside, thus cooling the space. Nonetheless, if the outside temperature is higher than the comfort zone it will increase the indoor temperature. In Babahoyo 4.0ach was calculated as the optimum rate. Figure 6 shows the impact of infiltration on thermal comfort on each UEM.

#### ***Orientation***

The optimum orientation was tested for the cardinal and ordinal directions. The results indicate that the best orientation for schools in Quito is with its main axis in North-South direction and the courtyard open to the south as to receive the highest amount of solar radiation; while in Babahoyo is with its central axis oriented opposite to the prevailing winds. The wind coming from the southwest cools down the classrooms, reaching 69.2% of occupancy hours in thermal comfort.

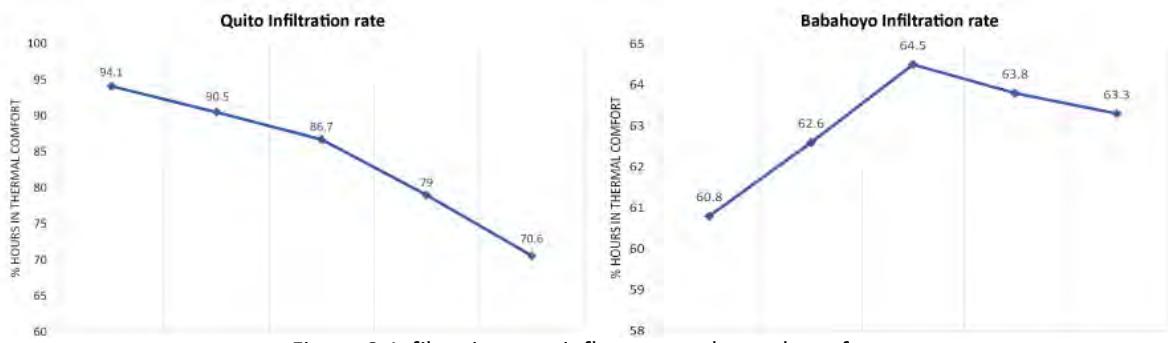


Figure 6. Infiltration rate influence on thermal comfort

### **Window to wall ratio (WWR)**

In Quito thermal comfort increase parallel to the increment in window's area. A WWR in external facades of 65% and 15% WWR in internal façade got the best performance. The increment in glazing's area makes the daylight factor increase an average of 1.7 points; therefore, the use of shading elements is recommended to control the intake of daylight.

The best results in Babahoyo were achieved with a WWR of 26% for outer façades and 15% for inner façades. By decreasing the original WWR from 34 to 26%, thermal comfort increases 1.9 points as solar radiation entering the space is limited.

### **Building fabric**

Thermal insulation is not used in the country and, as such, there are no regulations or recommendations on its use. Indoor thermal fluctuations are dependent on thermal mass and material densities. In Quito, the best thermal performance is obtained using 300mm thick medium density concrete blocks and by insulating all external walls; insulation improves thermal comfort on 1.8%.

In warm climates, the most efficient passive strategies were increasing the thermal mass to 677kg/m<sup>2</sup> (4.3% improvement), using ventilated roofs to prevent heat absorption (1.2% increase), and to provide shading in the central courtyard area (2.5% improvement). Insulating the building is not recommended as it increases the air tightness of the building.

### **Recommendations for each climatic region**

As Quito has primordially a cold-temperate climate, reducing the uncontrolled intake of cold air becomes essential to improve thermal comfort. Additionally, by increasing the window's size and orienting them towards the sun spaces are heated passively. The combined approach improves thermal comfort to 95.2% of occupancy hours, representing an increment of 24.6% from the original design.

Table 2. Optimum architectural passive strategies

Strategy	Optimum Value in Quito	Optimum Value in Babahoyo
Infiltration rate	0.5 ach	4.0 ach – night time vent
Orientation	NS	NW – SE
WWR external facade	65%	26%
WWR internal facade	15%	15%
Windows openable area	30% external 50% internal	90% external 90% internal
Building fabric	Medium weight blocks	Cast concrete
Insulation	100 mm	Double layer ventilated roof
Sun shading	Horizontal louvers	Shaded courtyard Overhangs

In warm climates ventilation is detrimental in controlling temperature, and as such, night time ventilation is recommended to expel the accumulated heat. Thermal comfort in Babahoyo increases from 63.8% of occupancy hours to 80.6% with the combined strategies. Table 2 shows the optimum values of each architectural parameter in both climates.

## Conclusions

The field measurements in classrooms yielded indoor temperatures between 17.3 and 20.3°C in Quito, and between 28.4 and 34.5°C in Babahoyo. These measurements were used to calculate the PMV and PPD indexes for each school. In Quito the PMV is -0.60 (slightly cold), and the PPD is 13.7%; while in Babahoyo the PMV is +2.0 (warm) and the PPD is 72.7%. The actual thermal sensation votes (TSV) were -0.63 and +0.44 for Quito and Babahoyo respectively, showing an overestimation of the PMV/PPD index.

In both UEMs the TSV showed an 87.8% of acceptance to their indoor conditions. This value reflects the acclimatization of students to their current conditions but do not reflect the levels of satisfaction to the indoor conditions. Students in Babahoyo qualified the indoor conditions as more satisfactory than the students in Quito due to the insanitary conditions of the former school. By using the optimum architectural parameters, thermal comfort can increase to 95% in Quito and 80% in Babahoyo.

## References

- ASHRAE, 2013. *Thermal environmental conditions for human occupancy*. Atlanta: ASHRAE.
- Auliciems, A., 1972. Classroom performance as a function of thermal comfort. *Int. J. Biometeor*, 16(3), pp. 233-246.
- Chatzidiakou, L., Mumovic, D. & Dockrell, J., 2014. *The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students*. 1st ed. London: The Barlett, UCL, Faculty of the Built environment .
- CITEC UBB, 2011. *Manual de Hermeticidad al Aire de Edificaciones*. Chile: Universidad del Bío-Bío.
- Fraser, B. J., 1994. Research on classroom and school climate. In: *Handbook of research on science teaching and learning*. New York: Macmillian, pp. 493-541.
- Humphreys, M. A., 1977. A study of the thermal comfort of primary school children in summer. *Building and environment*, Volume 12, pp. 231-239.
- Puteh, M., Ibrahim, M., Adnan, M. & Noh, M., 2012. Thermal comfort in classrooms: constraints and issues. *Procedia - Social and behavioral sciences*, Volume 46, pp. 1834-1838.
- Teli, D., Jentsch, M. & James, P., 2014. The role of a building's thermal properties on pupil's thermal comfort in junior school classrooms as determined in field studies. *Building and Environment*.
- Trebilcock, M., 2014. *Thermal comfort and energy efficiency in school buildings*. Nottingham, The university of Nottingham.
- Waldrip, B. & Fisher, D., 2003. Identifying exemplary science teachers through their classroom interactions with students. *Learning*, Volume 6, pp. 157-170.
- Zahiri, S., Altan & Hasim, 2016. The effect of passive design strategies on thermal performance of female secondary school buildings during warm season in a hot and dry climate. *Frontiers in Built Environment*, 2(3).
- Zomorodian, Z. & Nasrollahi, F., 2013. Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran. *Internation Journal of Architectural Engineering and Urban Planning*, 23(1), pp. 41-50.
- Zomorodian, Z., Tahsildoust, M. & Hafezi, M., 2016. Thermal comfort in educational buildings: a review article. *Renewable and Sustainable Energy Reviews*, Volume 59, pp. 895-906.



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*Design to Thrive*

## Performance-based Green Residential Building Evaluation and Design Tools and Method in Cold Climatic Zones of Northern China

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**Abstract:** This paper proposes and discusses an evaluation and design method in green residential buildings residing in the cold climate zones of Northern China. The national green building standard evaluation methods that are prevalent in China are technology based. The building performance and energy consumption in operational stages have not been controlled by the architect or used as a feedback within the initial design stage. This performance-based method introduces objective-effective design tools to assist the architect to consider energy efficiency during the entire design process. In this way, virtual environment simulation and post occupancy monitoring data of energy consumption (electricity and gas), indoor thermal environment of both winter and summer can be analysed and evaluated quantitatively when deciding to introduce or integrate any green building technology. This design method has been implemented and demonstration residential buildings projects were selected for this study. This performance-based method may help the architect to control the energy efficiency of residential buildings in operational stages.

**Keywords:** Performance-based, design tools and method, cold climate zones, green residential building,

### Introduction

The energy efficiency design standard for residential buildings was introduced in China in 1986. In the past 30 years, this design standard was updated in a four-stage, step-by-step process. Based on the building energy consumption levels during the 1980s, the energy levels were reduced by 30% in the first stage (1991~1999), 50% in the second stage (2000~2004), and 65% in the third stage (2000~2004). Beijing, a cold climate zone city of Northern China, successfully reduced the building heat loss from  $31.68\text{W/m}^2$  to  $14.65\text{W/m}^2$ . In the fourth stage (2010-present) design standard, the energy level should be reduced by 75 %. Although the improvements up until now were due to changes in the heating systems and buildings, there is potential to decrease levels with continuous building improvements. The effect of energy saving in the operational stage did not pair with the design standard and objective expectancy (Xia, 2015). To address this disparity, there must be new design method and tools to further energy efficiency.

This paper proposes a performance-based, objective-effective design method, which addresses the effect rather than the list of technologies utilized, and also pays more attention to the operational standard rather than the design standard. Design tools for virtual environment simulation, operation database, and post occupancy evaluation will be developed in the future. Design tools should evaluate the effectiveness of these strategies, technologies or integrations before they are actually selected and introduced in the design stage. This method may help to fill the gap between design and operation.

In China, previous standards such as the *Design Standard for Energy Efficiency of Residential Buildings to Severe Cold and Cold Zones* (JGJ26-2010) and the *Evaluation Standard for Green Building* (GB/T50378-2016) have been the design standard and are technology oriented. The newly launched *Standard for Energy Consumption of Building* (GB/T51161-2016), however, aim to be objective and effective oriented. This guide is regulated in operation by the heat energy consumption indicator, the constraint value, and the leading value. The building heating energy consumption indicators are a combination of building and heat distribution systems. They are determined separately according to the heating source in Table 1. The building heat demand indicators restrictions are shown in Table 2.

City	Energy consumption indicators(coal) [kgce/(m <sup>2</sup> · a) ]					
	constraint value			leading value		
Beijing	municipal central heating system	community central heating system	-	municipal central heating system	community central heating system	-
	7.6	13.7	-	4.5	8.7	-
Energy consumption indicators(natural gas) [Nm <sup>3</sup> /(m <sup>2</sup> · a) ]						
	municipal central heating system	community central heating system	household boiler	municipal central heating system	community central heating system	household boiler
	9.0	10.1	8.7	4.9	6.6	6.1

Table1 Building heat energy consumption indicators (coal or natural gas)

City	Building heat demand indicators GJ/(m <sup>2</sup> ·a)	
	constraint value	leading value
Beijing	0.26	0.19

Table 2 Building heat demand indicators

The advantage of the performance based design method that is supported by objective and effective connecting tools is that the measurement indicator is in operation and not just following restrictions in the design stage to verify the effect. In certain cases, technologies introduced in the design stage may actually have no effect at all.

## Methodology

The Procedure of performance based design method is depicted in Figure 1.

This method is fundamentally paying attention to the energy efficiency in operation stage rather than list of strategies introduced in design stage. The design tools of the database, the virtual environment simulation, the BIM (building information modelling), and the POD (post occupancy evaluation) enable the effects to be predictable and controllable, providing the architect with available support from the design to the construction. The tools will include the advantages of the existing simulation tools, or develop tools that address new demands in object analysis and design optimization. This will effectively predict judgement and decision making for the evaluation of the whole performance and technology integration within building diagnosis and occupant behaviour regulation for object setting and effect verification.

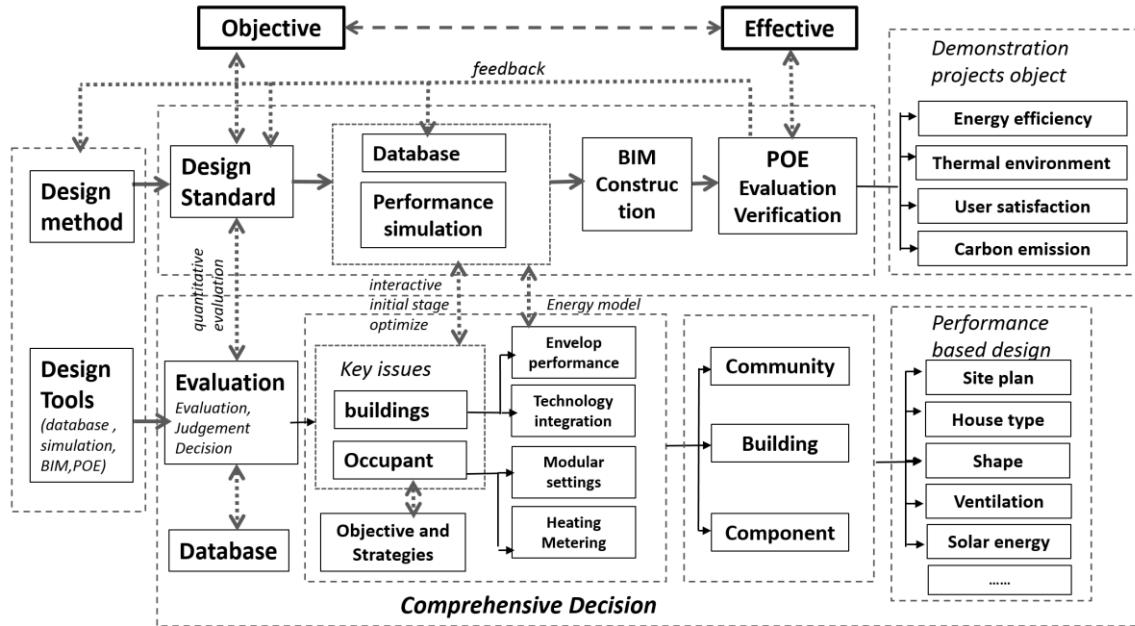


Figure 1 Technical route of proposed design method and tools.

### Key Issues and the Role of Design Tools

For residential buildings in Northern China's cold climate zones key energy efficiency issues include building related factors, such as building envelop performance, technology integration, and occupancy related factors, such as behavioural regulation and household heating and AC temperature settings. The survey of residential buildings in Northern China have shown that in some sample cities heating energy consumption was  $0.47 \text{ GJ}/(\text{m}^2 \cdot \text{a})$  with a heating source point of  $0.45 \text{ GJ}/(\text{m}^2 \cdot \text{a})$  in buildings, which was almost 35% higher than the average building heating energy requirements (Xia, 2015). This suggests that in addition to improving the building performance, occupant should also share responsibility in energy efficiency. The performance-based design tools will then consider factors of both building and occupant.

#### ***Building related factors***

##### ***Designs tools for building envelop performance***

Building envelop performance is particularly important for building energy efficiency in Northern China, where heating and AC accounts for the majority of the annual energy consumption. The heating period of residential buildings in cold zones is typically for six months during winter, and AC use is popular in the summer months. Performance improvement from the building envelop was both predictable and effective, as confirmed by the reliable Virtual Environment or energy consumption simulation tools. In the past 30 years, energy efficiency improvements have been mainly attributed to the building envelop, where there was a strict limitation of in shape coefficient, U value of wall, window to area ratio, and ensuring windows are air tight. The objective of the fourth stage standard of energy consumption was a further reduction by 75 %. Although a further reduction of the wall U value can be effective, the potential of the U value is diminished. However, construction and detailed design of the thermal bridge, high quality frames, and double or triple coated glass windows do deserved consideration. Many virtual environment and energy simulation software suites can accomplish this job, however, it is necessary to develop more

comprehensive tools for the performance based design method, which considers more building factors.

#### *Designs tools for Technology and Integration*

Building virtual environment and simulation tools are effective in predicting the effectiveness of energy efficiency technology, but are less effective in predicting the effectiveness of technology integration in a building energy model. There has been variety of active or passive technology used, including solar energy used in room heating and hot water supply, BIPV, and wind turbines are used as substitutions for fossil fuel energy. Additionally, there are many passive technologies, such as natural ventilation cooling or solar shading devices. These energy efficient technologies should be evaluated separately to verify their effectiveness. If they are not evaluated separately it would be impossible to know the true effect of the individual technology. In this case, building simulation tools should provide architects with quantitative evaluation and effectively predict outcomes of integration.

#### *Occupant related factors*

Occupancy is a variable that is uncertain and cannot be easily predicted. Neither the mechanism nor influence from the occupant is clear, in most cases these factors cannot be evaluated quantitatively as they are for building related factors.

Regulating occupant behaviour will be beneficial to energy saving. It is clear that energy consumption of the same residential unit varied depending on the occupant. Patterns of occupant behaviour (laundry frequency, AC temperature settings) and household model (space adaptive usage, division heating and AC control) have potential effectiveness on energy efficiency. Previous research attempted to relate the energy consumption with individual characteristics of the behaviour, for example household room heating temperature setting (Liu, 2015). Further energy saving effects are supported by simulation tools and POE database of the occupant related factors. Household automatic settings metering and adjustment heating systems will encourage and regulate energy efficiency behaviour among occupants.

#### *Behaviour regulation by modular settings*

Modular settings and automatic control of thermal environments is an easy way to regulate behaviour, and should reduce incorrect operation. Modular settings will be easy to operate, and will reduce disruption of services and uncertainty relating to the amount of usage. The objective of modular settings was a more precise and separate control for heating and AC equipment that would have division control, and could be adjusted according to household daily/weekly/monthly/yearly schedule of occupants. Modular settings can be adjusted by occupants themselves or automatically by indoor human localization based on distribution infrared red Sensor networks or monocular videos.

#### *Household metering and adjustment heating system*

The higher standard found within the *Standard for Energy Consumption of Building (GB/T 51161-2016)* was primarily from heating sources, distribution systems, and buildings. In Northern China, municipal central heating systems are the normally used in residential communities, and household overheating often occurs. The heating system is controlled solely by a central heating source rather than the individual households needs. Even when temperatures reach 25°C indoors, the occupant can do nothing other than open a window. This results in energy waste and heat loss. Since heating and AC demands vary between households, energy can be conserved by implementing heating load metering systems for

each unit with adjustable heating and AC settings. The design and matching of the heating system will be implemented and supported by the database and simulation tools.

### **Performance Based Comprehensive Design Tools**

Building performance improvement is dependent on the comprehensive design tools during evaluation, simulation, analysis, decision-making, and verification of the building envelop performance, effective use of technology, and the potential of occupant behaviour regulation with household metering systems.

The design tools will extend the field of existing knowledge to meet the demand of performance-based design within their analysis, decision, and verification evaluation. This is for architect and engineer, for occupant and heating system manager. It enables effect prediction at any stage during the process, by using as much data as you have available, and in as much detail as desired. This also sets stringent standard and objective measures, which cover a wide range of building information at any stage ranging from the initial stage to the detail calculation or the detail design.

#### ***The procedure and role of design tools***

The performance based design tools was used the whole process of design stages, in strategy analysis, technology selection, effect simulation, optimum decision, implementation and POE.

These database tools will be constructed on the basis of the monitoring data of sample existing residential building in operation. These simulation tools will be used for comparative study and decision making of technology and integration. These tools are a combination of database, simulation, BIM and POE, offering support in object setting, effect prediction, analysis, judgement and decision, evaluation, and lastly, verification. Simulation tools used for quick calculation for the initial stage and precisely simulation and decision in the design stage. BIM tools used in the construction stage. POE tools used for quantitative evaluation and measurement in operation stage and effect verification.

These will provide quantitative support in effectively evaluating the conventional technology, as well as new technology that addresses the buildings and the occupants, the design optimization, the prediction and decision-making, the initial design and the detail design, as well as the summer mode and winter mode to ensure the objective is achievable.

The database, baseline, and object data provided relates to existing residential building in operation. The constrain value and leading value in the *Standard for Energy Consumption of Building (GB/T51161-2016)*, are based on a survey of existing buildings.

#### ***Decision making tools***

The objective-effective tools attempt to determine via POE why some technology was integrated effectively, while others were not. Some possible explanations are that the technology itself was proven effective. Proving effectiveness is necessary otherwise it should be excluded. The chosen technology could be ineffective depending on the climate, occupant, or the specific building. In this case, alternative technology should be used. It could also be the case where there is conflict among the technologies that are implemented. The occupant may also make mistakes if they do not operate or manage the technology correctly.

Technology decisions must be made both quantitatively and qualitatively, as there are many factors to consider. For the factors that can be evaluated quantitatively, such as the U value of building envelop, heat loss and indoor thermal environment, effect of the solar

shading device, natural ventilation, and CFD optimization. Additional tools will be developed to effectively evaluate occupant behaviour.

### ***Effect verification tools***

In performance based design, only technologies that were effective or are potentially effective will be selected and integrated. The effects are predicted by simulation tools or the database of their POE effectiveness in existing buildings. The prediction of effect and the identification and verification of effect of specific technology is problematic. The database not only contained the results of surveys for existing residential buildings, but also cover a variety of information that indicates the relationship between technology and effectiveness, such as plan and section design, space area and height, space division of living, sleeping, and the kitchen in household model, or such as passive energy efficiency technologies integrated in staircase, sunspace and balcony. The indoor thermal environment is manipulated with window opening and solar shading devices. The U value and the thermal mass of building envelop manipulated the summer and winter insulation improvement, the air gap, and the windows insulation. Some could not be identified with a specific technology, so simulation tools may be of use.

### **Case Study: Demonstration Projects**

The above method is being implemented in demonstration projects in Beijing. Tools used in the design stage for strategies include design optimism and technology integration. The construction will finish in 2019, when a post occupancy evaluation for the effect verification can be performed.

### ***Analysis and optimizing in design stages***

The analysis focused on objective, risk assessment, challenge, and objective-effective variation. The simulation and optimizing research in progress were implemented in the planning, layout management, household models design, and building envelop performance promotion, which was confirmed by simulation tools of thermal environment and energy.

#### ***Object, risk assessment and challenge analysis***

The object set for demonstration projects. In China, residential buildings construction will conform to the 4<sup>th</sup> stage standard by design starting in 2010. By 2016, they will follow the basic requirements of building heat demand indicator found in the *Standard for Energy Consumption of Building (GB/T51161-2016)*. This will use the effect measured by value of the energy consumption indicator, with the constraint value equal to the index of heat loss found during the 2<sup>nd</sup> stage level (JGJ26-95), and the leading value is equal to the index of heat loss found during the 3<sup>rd</sup> stage level (JGJ26-2010). In Beijing, the constraint value and leading value of building heat demand indicators are 0.26 GJ/(m<sup>2</sup>) and 0.19 GJ/(m<sup>2</sup>· a)(Xia,2015).The demonstration projects will have an additional 30% energy efficiency over the constraint value of the energy consumption indicator. There are two steps present, from the constraint value to the leading value, and then from the design value to the operation value. According to the preliminary estimation of our research group, in Beijing, the 3<sup>rd</sup> stage thermal heating index (W/m<sup>2</sup>) standard nearly met the objective of 30% improvement in the demonstration projects. The energy consumption indicator increased from 0.26 GJ/( m<sup>2</sup> · a) (2<sup>nd</sup> stage, constrain value) to 0.19 GJ/( m<sup>2</sup> · a) (3<sup>rd</sup> stage, leading value) by 26.9%(>30%). There may be a further improvement of 28.3 % from the 3<sup>rd</sup> to the 4<sup>th</sup> stage. Calculations indicate that it will match the objective of the 4<sup>th</sup> stage thermal heating index. The thermal heating index

value for residential buildings (floor lever over 14) was restricted to 10.50 W/m<sup>2</sup>. The objective of demonstration projects (8.245 W/m<sup>2</sup>) will match the current standard during the 4<sup>th</sup> stage local standard of Beijing ( 8.5W/m<sup>2</sup>, equals to 0.26 GJ/(m<sup>2</sup> • a)).

#### *Effectiveness evaluation, judgement and decision-making*

Technologies integrated for Buildings. In the design stage of demonstration projects, simulation tools of energy and thermal environment were utilized for energy strategies in communities planning, household model, building envelop and energy system. In the optimization simulation of heat land, shape coefficient, plan, elevation, section, building envelop performance, the U value of window and thermal bridge (roof, overhead, rooms adjacent to non-heating room, door and balcony).Besides, more and more additional technologies were introduced and integrated after simulation and judgement, such as external shape for enhanced natural ventilation, daylighting ,plan and section for natural ventilation and wind scoop, double skin space, BIPV, building integrated solar heating collection, storage and distribution system and heating recovering system.

Automatic setting and operational instructions provided for occupants. To reduce the disturbance of occupant, information of the lifestyle and time schedule of routine life will be used as reference in space heating and AC modular settings. Database of existing residential building was under construction now, giving advice and guidance to those occupant who are interesting in energy efficiency.

#### ***The POM schedule of verification***

The purpose of the POM is to verify of effectiveness by monitoring the household energy thermal environment and energy consumption. Sub branches of electricity consumption of lighting, socket (non AC or heating), heating and AC (occupant and building performance) will be measured separately. Gas for cooking, hot water, and heating will be measured separately for comparatively analysis, effect verification of a specific technology, integration, or behaviour diagnosis. This will promote further building energy performance enhancement by correlation analysis and sensibility analysis. It will regulate household behaviour via a time schedule, thermal environment settings, and window opening, and habits and activities related to energy, so that the household can be managed in a more controlled and sensible state, via a auto infra sensor or intelligent controlling system. Intelligent controlling systems can recognise the statue, habits, and routines of the occupants' daily. The POE will provide information on the buildings and occupants for an increase in energy efficiency and reducing waste.

#### **Conclusions and Prospective Work**

A performance based energy efficiency residential building design method is proposed in this paper to meet the standards of *Energy Consumption of Building (GB/T51161-2016)*. This will benefit the architect in dealing with key building and occupant factors in cold climate zones in Northern China. Design tools will also be developed to determine object-effect analysis, evaluation, judgement, and decision-making across the design during construction and operation stages. This method has been implemented in demonstration projects in objective, risk assessment, challenge analysis and design optimize. The proposed Post Occupancy Evaluation will verify the effectiveness of these demonstration projects post construction and the results will provide feedback and information for validation of these design method and tools.

## Acknowledgements

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## References

- GB/T50378-2016. Evaluation Standard for Green Building[S]. Beijing: Ministry of Housing and Urban-Rural Development of People's Republic of China. 2016, in Chinese
- GB/T51161-2016. Standard for Energy Consumption of Building[S]. Beijing: Ministry of Housing and Urban-Rural Development of People's Republic of China. 2016, in Chinese
- JGJ26-2010. Design Standard for Energy Efficiency of Residential Buildings to Severe Cold and Cold Zones [S]. Beijing: Ministry of Housing and Urban-Rural Development of People's Republic of China. 2010, in Chinese
- J. Xia, Y. Jiang, the determination of heating indicator in domestic building in Standard for Energy Consumption in China, Construction Science and Technology, 2015, vol14 , in Chinese)
- N.Liu, D.Mo, M. Wang, J.Zhang. Social technical analysis of urban household residential carbon emissions in China [J]. Journal of Tsinghua University (Sci & Technol ), 2015, Vol.55.No.9, in Chinese
- N.Liu, D.Mo, J. Zhang, S. Zhao, M. Wang. Evaluation of Occupant Behavior in Summer Air Condition Use and Household Energy Consumption, School of Architecture, Tsinghua University, Beijing, China. PLEA 2016 Los Angeles - 36th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A long term parameter dataset for calibration of low energy building retrofit models for education and research

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**Abstract:** Robust retrofitting is integral to reducing the energy consumption of the existing building stock. Simulation plays a key role in determining the most effective retrofit solution for a particular building. While many synthetic test cells provide an environment to validate whole building simulation tools, calibration reflects the real operation of buildings and can produce more reliable models. A calibrated tool that can assess whole building energy and thermal comfort could be a powerful aid in decision making and policy formation in many countries. However, there often exists a lack of detailed information and data about the real operation of existing buildings in order to perform detailed calibration. This paper presents a long term dataset of parameters collected in a live low energy building retrofit test-bed in Cork, Ireland (NBERT/zero2020). The retrofit strategy consists of ventilative cooling and mechanical heating. Long term performance indicators for energy consumption and thermal comfort are presented. The dataset allowed for the creation of an open source online data portal available for use by the building research community. The online dataset provides information related to the building test-bed as well as long term measurement data and can support model calibration efforts by researchers, designers and educators.

**Keywords:** data portal, energy, retrofit, education

### Introduction

High levels of retrofitting will be required in the coming years in order to achieve European carbon emissions targets. Although certain countries have retrofitted a number of buildings (Dennehy and Howley, 2013), deep renovations may be required to meet a targeted 90% reduction in building energy consumption by 2050 (European Commission, 2011). In Ireland, the public sector has targeted an improvement of 33% in energy efficiency by 2020 (Department of Environment Community and Local Government, 2012), with a 21% improvement achieved in 2015 (SEAI, 2015). However, energy is not the only demand placed on the modern built environment. As people are expected to spend 60 to 90% their lives indoors (Kunkel *et al.*, 2015) the demand for a healthy built environment has also increased. To quantify the effects of retrofitting accurately energy and comfort modelling is required. A whole building energy and comfort model can appropriately account for both energy and comfort demands in modern buildings. Many whole building energy simulation tools have been validated for use in the area of energy consumption simulation (Lomas *et al.*, 1997). However, when these tools are not calibrated discrepancies between actual and simulated energy consumption of  $\pm 30\%$  are seen (Ahmad and Culp, 2006). One of the main issues associated with building energy and environmental simulations is related to their complexity (Fabrizio and Monetti, 2015). Whether a manual or automated approach is

adopted for model calibration, a large quantity of data is often required or some data may not be available for a given building (Coakley, Raftery and Keane, 2014). The challenge for the building model calibrator can also lie in the scale of data collected in a building and the quality of the data generated. Ideally a researcher or student would begin at a small scale when beginning to grasp the calibration of a model. Looking at a smaller building first could aid in understanding the data needed from larger buildings. Test-cells are small in scale, have been widely published (Clarke, Strachan and Pernot, 1993; Mateus, Pinto and Da Graca, 2014) and can allow the research community validate models and guarantee a certain level of quality in results. However, test-cells are unoccupied and as calibration attempts to capture the real performance of a building (Snyder and Maor, 2015) an occupied building is necessary. Existing datasets on real buildings contain information related to long term building energy consumption and thermal comfort (US, 2017). However, these buildings are typically large in scale and may not have enough detailed information to allow a researcher to calibrate to both basic and detailed levels, from Level 1 to Level 5 (Fabrizio and Monetti, 2015). The other key issue with data on either test-cells or real buildings is the ease in accessing it and the lack of functionality in accessing only part of the datasets. Typically you can download an entire dataset for a year or more (Nore *et al.*, 2007) but you may only require a fraction of that data. A web-based open source dataset from an occupied building, of a manageable scale, with added selection functionality, and with detailed information would be both student suitable and researcher friendly. This paper presents a long term energy and thermal comfort parameter dataset that was accumulated from a retrofitted low energy building in Cork Institute of Technology, Ireland. Initially, information on the building's properties and information related to its operation and design are presented. This is followed by information on the data gathering process used to create the dataset. A selection of the dataset is used to show the long-term energy performance and thermal comfort performance of the building. An accessible beta-version of an open source interactive web portal for students and researchers was also created using the dataset. It is intended that a fully functional version of this web portal will be accessible within six months of this publication.

## Materials and Methods

### ***Building background and information***

The National Built Energy Retrofit Test-bed (NBERT) is a 223m<sup>2</sup> educational building that is part of the wider Cork Institute of Technology (CIT) main campus in Bishopstown, Co. Cork, Ireland. The NBERT building is a renovated part of the existing CIT main campus building which was designed in 1974 (O' Sullivan *et al.*, 2010). The retrofit project was completed in 2012 and now functions as live test-bed for research activities for micro-grid (Asaleye and Murphy, 2016), ventilation (O' Sullivan and Kolokotroni, 2016) and thermal comfort applications (O' Donovan, O' Sullivan and Murphy, 2017). Figure 1 provides some information regarding the layout of NBERT as well as information on the automated ventilation openings and the location of some sensors in the building. The main orientation of the building is west facing where the surrounding buildings are of the same height. The building has mostly unobstructed views to the northwest and southwest but does have a building obstructing the west façade. Information on the buildings thermal properties are indicated in Table 1. Table 2 provides information as to the installed equipment and lighting

loads, as well as the presence of exposed thermal mass in certain rooms in the building. The ECG19 benchmarks (Energy, 2000) are also referenced for comparative purposes. The building is open from 08:00am to 10:00pm daily during each academic semester.

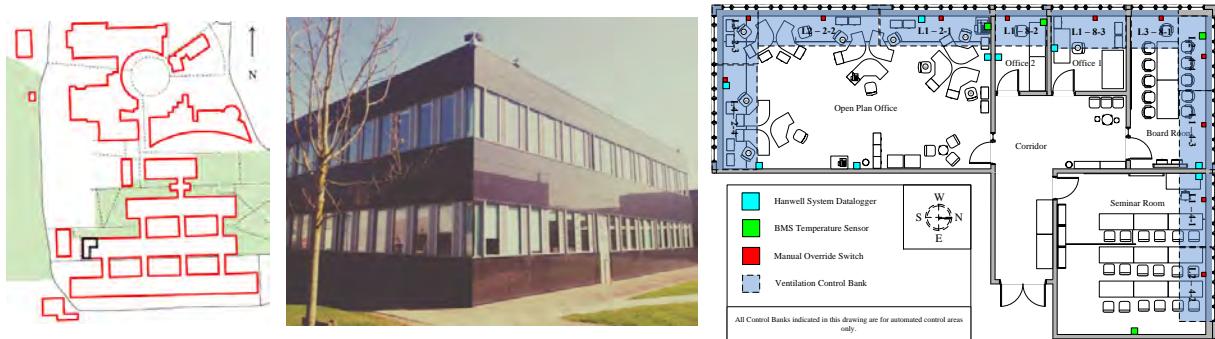


Figure 1: NBERT building from left to right: location in relation to CIT campus, exterior of building, plan view of building including ventilation banks and sensor locations

Table 1: NBERT thermo-physical properties for key building elements

Element	U-value (W/m <sup>2</sup> K)	Construction	Location
Roof	0.09	200mm Kooltherm insulation, 150mm Concrete Slab, 25mm cork insulation, 5mm Asphalt coating	Flat roof
External Wall	0.09	100mm Internal Block, 86mm BASF Walltite spray foam, 125mm Aggregate panel, 30mm Air gap, 125mm KS1100 insulation, 37mm Air gap, 12mm granite ceramic panel	Wall to exterior
Triple glazed window	0.98	4mm Saint Gobain Low-e Planitherm Total +, 16mm 90% Argon filled gap, 4mm Saint Gobain Low-e Planitherm Total +, 16mm Argon filled gap, 4mm Saint Gobain Plainlux clear float	Board room, Seminar room
Quadruple glazed window	0.86	4mm Saint Gobain Low-e Planitherm Total +, 16mm 90% Argon filled gap, 4mm Saint Gobain Low-e Planitherm Total +, 16mm Argon filled gap, 4mm Saint Gobain Plainlux clear float, 24mm air gap with 16mm interstitial venetian blind, 4mm clear float	Open plan office, Office 1 and Office 2
Floor	0.78	150mm Cast concrete slab	1 <sup>st</sup> floor to Ground floor

Table 2: Maximum occupant, lighting, equipment densities and presence of exposed mass in building zones

Location	Area (m <sup>2</sup> )	Floor-to-ceiling (m)	Occupant density (m <sup>2</sup> /p)	Lighting density (W/m <sup>2</sup> )	Equipment (W/m <sup>2</sup> )	Exposed ceiling (Y/N)
Open Plan Office	88	2.7	7	12.9	43.4	No
Office 2	9	2.7	9	13.3	0.0	No
Office 1	12	2.7	12	22.8	44.5	No
Board Room	25	2.7	3	12.5	3.8	No
Seminar Room	54	3.24	3	8.7	5.9	Yes
Corridor	34	3.24	N/A	6.7	3.6	Yes
ECG19 Benchmark	N/A	N/A	N/A	10-14	12-18	N/A

### ***Operation and building energy systems***

The heating system comprises of a Dimplex LA 28AS air-to-water heat pump with a maximum heating power output of 28kW at a quoted COP of 3.6 (10°C ambient air

temperature & 35°C supply water temperature). The supply temperature for heating is weather compensated using the average of three ambient temperature sensors. Heat is delivered to the building via low surface temperature radiators with a temperature regulating valve for each radiator. The heating system operates on time schedules which depend on the academic calendar. The building relies on natural ventilation for both cooling and indoor air quality. The main source of natural ventilation is single sided with some instances of cross flow ventilation. There are a total of 72 individual ventilation openings in the building, 32 are manually operated (low level) and 36 are automated (high level). The high level openings in the building indicated in Figure 1 are grouped into banks and controlled on a zone setpoint of 21°C, a night cooling zone setpoint of 15°C, and an external temperature limit of 10°C. Each ventilation bank consists of between two and four openings which area positioned above head height. There are also manual override switches for each of the ventilation banks as shown in Figure 1. The building also generates and receives renewable energy from a solar PV array on the roof and a wind turbine nearby. For more information on this see (MESSO Research Group, 2017a).

### **Data gathering and processing**

The NBERT building has capabilities in monitoring and gathering internal parameters from both a typical BMS as well as a more detailed Hanwell internal environmental monitoring system. The BMS allows for the monitors and gathers data on internal air temperatures, energy consumption for general services, lighting, and the buildings air source heat pump. It also measures the position of actuators for the natural ventilation system in the building. Externally, NBERT has an on-site weather station located on top of the building at a height of 5m above roof level. Tables 3 and 4 provide more detail as to model type, accuracy and logging interval of internal and external instruments. To create the dataset used in the online data portal data is gathered from the three main sources and stored in a local hard drive.

Table 3: Instrument accuracy and logging intervals for internal data logging systems

Parameter	Instrument/System	Specification information
Temperature	Hanwell 4002T	±0.1°C (-10°C to 40°C)
Humidity	Hanwell 4115RHT	±2% (0%-90%) ±3% (90%-100%)
CO <sub>2</sub> Temperature	Hanwell Climabox 3 TE-RT, BMS	±50ppm (0 – 4000ppm) ±0.2°C (-20°C to 60°C)
Energy	Socomec DIRIS A20	Class 0.5S, EN- IEC 62053-22
Ventilation Position	BACnet Windowmaster	(0 – 100%)

Table 4: Instrument accuracy and logging intervals for external weather station

Parameter	Instrument/System	Specification information
Temperature	HC2S3 Rotronic Hygroclip 2 probe	±0.1°C at 23°C
Humidity	HC2S3 Rotronic Hygroclip 2 probe	0.8%RH at 23°C
Air Pressure	Vaisala PTB101B	±0.5mb at 20°C
Solar Radiation	Campbell Sci SP1110 Pyranometer	±5% for 350–1100nm /linearity 1% dev
Wind Speed	Campbell Sci 05103 Vane Wind Monitor	±0.3 ms <sup>-1</sup> or 1% of reading (0-100 ms <sup>-1</sup> )
Wind Direction	Campbell Sci 05103 Vane Wind Monitor	±5.0°
Daylight Levels	Skye SKS 1110 Pyranometer	0-5000W/m <sup>2</sup> / typ. <3% cal err
Rainfall	EML Aerodynamic rain gauge ARG100	0.2mm/tip

The local BMS system uses Unitron report software to log data related to the building and Unitron datalog manager software to select and download data. The Hanwell system uses Hanwell RadioLog software to view and download data from wireless data loggers. Data from the Campbell Scientific weather station is collected and appended in file locally using Loggernet software. The Unitron system stores files locally in the BMS computer which has all daily datalogs for each parameter measured. The Hanwell system does not have files that are easily accessible to users. Data must be selected and downloaded from RadioLog in order to create an entire internal environmental dataset. The weather data is stored in one file that is appended once the data logger is connected. All data collected for each individual dataset was collected using a “read\_bulk” function in RStudio (Kieslich and Henninger, 2016). Along with the three main datasets highlighted above additional data for Cork Airport was downloaded from (Met Éireann, 2017). In order to get the data in a useful format each dataset required processing. For most datasets this meant; formatting date and time entries correctly, changing data types, deleting duplicates, ordering data correctly, merging, as well as subsetting in order to produce a dataset that could be used with the online data portal. Once processing was complete it was considered fit for use as a model calibration dataset.

## Results and Discussion

### *Energy consumption data*

The energy consumption of the building is metered in four main areas; general services, lighting, heat pump and a circulating pump for the heating system. From Figure 2 it can be seen that the typical energy consumption is less than 90kWh/m<sup>2</sup>/a. This is over a 56% energy reduction in delivered energy terms in comparison to the old building (Cork Institute of Technology, 2017). The heating system energy consumption is less than the PassiveHaus criteria for specific heating demand of 15kWh/m<sup>2</sup>/a.



Figure 2: Observed annual energy consumption for NBERT between 2014 and 2016 (left), and percentage of monthly energy consumption during 2016 (right).

While the percentage of consumption varies monthly, general services and lighting can account for over 70% of the energy consumption in most months. With greater than 75kWh/m<sup>2</sup>/a attributed to electrical energy consumption improvements could be made. One option could be to adopt the ECG19 benchmarks for installed electrical equipment. Currently the average installed equipment power density is 22W/m<sup>2</sup> reducing this to the benchmark levels indicated in Table 2 would reduce consumption further.

### **Thermal comfort data**

NBERT operates typically in free running mode with infrequent use of its air source heat pump. In Cork, there is a lot of potential to naturally ventilate with over 80% of the exponentially weighted external temperatures observed between 2013 and 2016 data between 5°C and 20°C. The general comfort performance of the building is good, when using the adaptive comfort standard EN 15251 (NSAI, 2007), with 80-90% of occupied comfort recordings were in category III or higher. Generally, the percentage of occupied comfort recordings in category IV seldom exceeds 17%, as is shown in Figure 3. The majority of incidences in category IV were due to overcooling as opposed to overheating.

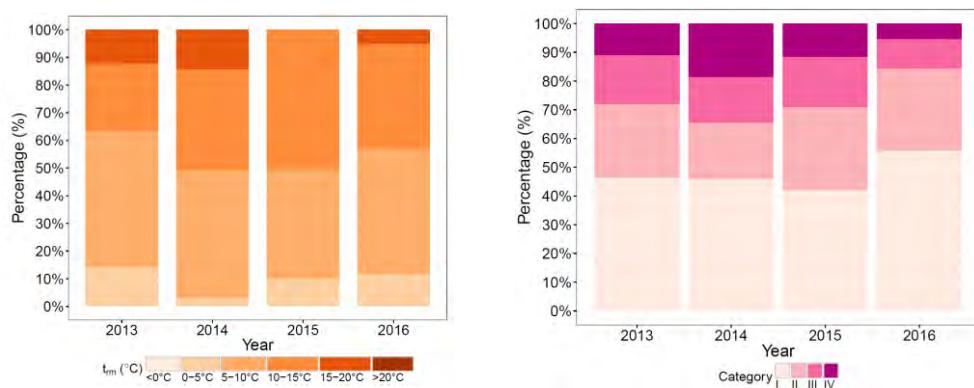


Figure 3: Percentage of exponentially weighted mean external temperatures for Cork Airport from 2013 to 2016 (right), performance with regard to the adaptive standard EN 15251 (left) assuming an occupied building from 09:00am to 17:00pm throughout the year

### **Data portal**

Although currently in its infancy the NBERT data portal is an online RShiny application which allows for the interactive visualisation of data in a web-based platform, using the open source language in RStudio. One of the main benefits of RShiny aside from being open source is that no prior knowledge of typical web development languages is required to make an interactive webpage. The data portal contains within it all the data related to and from the NBERT building systems. Initially collected and stored in a local database, it is also backed up online through Google Drive. This data is then manipulated and wrangled using code in RStudio to get it into a format that is appropriate for use in the data portal. A full version of the data portal is expected to be completed in the next six months. However, a beta version of the web portal using a selection of weather data and internal data only can be found at (MeSSO Research Group, 2017b). Table 5 provides information as to what data is available at a particular interval in a given year, for each of the main data gathering systems. The data portal is expected to have two main functions; an interactive information portal and a relational database. The interactive information portal will contain information related to the NBERT building design, thermo-physical properties, measurement instrumentation and energy systems. This is expected to complement the long term data in the relational database. The information presented will be in an easy to use format and can be readily accessed by researchers developing models for similar applications, by educators and researchers looking to source data for project based learning, and for policy makers wanting to know more about validated passive retrofit solutions. The relational database will contain data at the various sampling intervals as indicated in Table 5.

Table 5: Sample of the available data by data type, interval and year

Year	Interval (min)	BMS		Weather Station		Hanwell Internal	
		Available (Yes/No)	%	Available (Yes/No)	%	Available (Yes/No)	%
2013	60	Yes		Yes	80	Yes	
	30	Yes		Yes	63	Yes	
	15	Yes	70	Yes	55	No	80
	10	No		Yes	53	Yes	
	5	No		Yes	50	No	
2014	60	Yes		Yes		Yes	
	30	Yes		Yes		Yes	
	15	Yes	88	Yes	77	No	87
	10	No		Yes		Yes	
	5	No		Yes		No	
2015	60	Yes		Yes		Yes	
	30	Yes		Yes		Yes	
	15	Yes	77	Yes	89	No	98
	10	No		Yes		Yes	
	5	No		Yes		No	
2016	60	Yes		Yes		Yes	
	30	Yes		Yes		Yes	
	15	Yes	97	Yes	55	No	84
	10	No		Yes		Yes	
	5	No		Yes		No	

## Conclusions

This paper has presented a dataset of energy consumption and thermal comfort measurements from a low energy office building retrofit in Cork, Ireland. It presents information on the buildings: location, thermo-physical properties, and zone-by-zone properties. Details about the data gathering process was described, including the relevant instrument specifications for internal and external instruments. A selection of the dataset was used to demonstrate the long-term energy consumption performance and thermal comfort performance of the building. This indicated good standardised thermal comfort performance with incidences of overcooling, while improvements in equipment energy consumption could be made. A beta-version of a web portal was created and the percentage of available data from each source conveyed. The paper outlines the intentions to create a fully functional relational database and data portal within the next six months.

## References

- Ahmad, M. and Culp, C. H. (2006) 'Uncalibrated Building Energy Simulation Modeling Results', *HVAC&R Research*, 12(4), pp. 1141–1155. doi: 10.1080/10789669.2006.10391455.
- Asaleye, D. and Murphy, M. D. (2016) 'Monetary savings produced by multiple microgrid controller configurations in a smart grid scenario', *IEEE EnergyCon 2016*.
- Clarke, J., Strachan, P. A. and Pernot, C. (1993) 'An approach to the calibration of building energy simulation models', *Transitions-American Society of Heating Refrigerating and Air Conditioning Engineers*, (Judkoff 1983), pp. 917–930.
- Coakley, D., Raftery, P. and Keane, M. (2014) 'A review of methods to match building energy simulation models to measured data', *Renewable and Sustainable Energy Reviews*. Elsevier, 37, pp. 123–141. doi: 10.1016/j.rser.2014.05.007.

Cork Institute of Technology (2017) *Zero2020energy.com*. Available at: <http://www.zero2020energy.com/> (Accessed: 7 June 2017).

Dennehy, E. and Howley, M. (2013) *SEAI: Energy in the Residential Sector 2013*. Available at: [http://www.seai.ie/Publications/Statistics\\_Publications/Energy-in-the-Residential-Sector/](http://www.seai.ie/Publications/Statistics_Publications/Energy-in-the-Residential-Sector/).

Department of Environment Community and Local Government (2012) 'Towards Nearly Zero Energy Buildings In Ireland Planning For 2020 and Beyond', *Towards Nearly Zero Energy Buildings in Ireland*, (November), p. 55.

Energy, A. (2000) *Energy Consumption Guide 19*.

European Commission (2011) *COMMUNICATION FROM THE COMMISSION: A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final*. doi: 10.1002/jsc.572.

Fabrizio, E. and Monetti, V. (2015) 'Methodologies and advancements in the calibration of building energy models', *Energies*, 8(4), pp. 2548–2574. doi: 10.3390/en8042548.

Kieslich, P. J. and Henninger, F. (2016) *Read\_bulk*. Available at: <https://cran.rstudio.com/web/packages/readbulk/readbulk.pdf>.

Kunkel, S., Kontonasiou, E., Arcipowska, A., Mariottini, F. and Atanasiu, B. (2015) *Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations*.

Lomas, K. J., Eppel, H., Martin, C. J. and Bloomfield, D. P. (1997) 'Empirical validation of building energy simulation programs', *Energy and Buildings*, 26(3), pp. 253–275. doi: 10.1016/S0378-7788(97)00007-8.

Mateus, N. M., Pinto, A. and Da Graca, G. C. (2014) 'Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell', *Energy and Buildings*, 75, pp. 511–522. doi: 10.1016/j.enbuild.2014.02.043.

MeSSO Research Group (2017a) *Messo Research Group CIT*. Available at: <http://messo.cit.ie/nbert> (Accessed: 4 June 2017).

MeSSO Research Group (2017b) *NBERT data portal*. Available at: <https://zero2020aod.shinyapps.io/App-1/> (Accessed: 4 June 2017).

Met Éireann (2017) *Met Éireann Climate Request (Historical Data)*. Available at: <http://www.met.ie/climate-request/>.

Nore, K., Blocken, B., Jelle, B. P., Thue, J. V. and Carmeliet, J. (2007) 'A dataset of wind-driven rain measurements on a low-rise test building in Norway', *Building and Environment*, 42(5), pp. 2150–2165. doi: 10.1016/j.buildenv.2006.04.003.

NSAI (2007) 'IS EN 15251 - Indoor Environmental Input Parameters For Design And Assessment Of Energy Performance Of Buildings Addressing Indoor Air Quality, Thermal Environment, Ligthing And Acoustics'.

O' Donovan, A., O' Sullivan, P. D. and Murphy, M. D. (2017) 'A field study of thermal comfort performance for a slotted louvre ventilation system in a low energy retrofit', *Energy & Buildings*. Elsevier B.V., 135, pp. 312–323. doi: 10.1016/j.enbuild.2016.11.049.

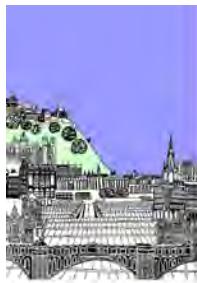
O' Sullivan, P. . D. and Kolokotroni, M. (2016) 'Non dimensional analysis and characterisation of driving forces for a single sided slot louver ventilation system', *International Journal of Ventilation*, 14(4), pp. 335–348. doi: [doi.org/10.1080/14733315.2016.11684091](https://doi.org/10.1080/14733315.2016.11684091).

O' Sullivan, P. D., Delaney, F., O' Riain, M., Clancy, T., O' Connell, J. and Fallon, D. (2010) 'Design and Performance of and External Building Envelope Retrofit Solution for a Grid Optimised Concrete Structure: A Case Study', in *30th International Manufacturing Conference*, pp. 1–12.

SEAI (2015) *Annual Report 2015 on Public Sector Energy Efficiency Performance*. Available at: [http://www.seai.ie/Publications/Your\\_Business\\_Publications/Public\\_Sector/Annual-Report-2015-on-Public-Sector-Energy-Efficiency-Performance.pdf](http://www.seai.ie/Publications/Your_Business_Publications/Public_Sector/Annual-Report-2015-on-Public-Sector-Energy-Efficiency-Performance.pdf).

Snyder, S. C. and Maor, I. (2015) 'Calibrated Building Energy Simulation in Practice: Issues, Approaches, and Case Study Example.', *ASHRAE Transactions*, 121(2), pp. 1–8. Available at: <http://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=108334650&site=ehost-live>.

US, D. of E. (2017) *Open Energy Data*. Available at: <https://energy.gov/data/open-energy-data>.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Analysis of comfort in multi-family housing in Madrid, Spain (1940- 1980). Four case studies monitored for energy rehabilitation

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**Abstract:** Considerable areas of Spain's major cities are occupied by social housing built between the end of the its Civil War (1939) and the late nineteen seventies. These dwellings, erected prior to the enactment of the earliest provisions on thermal conditioning (NBE CT 79), are largely non-compliant with current energy standards, with the concomitant energy dissipation, lack of indoor comfort and unnecessary expense. In Madrid, 58 % of all dwellings were built before the advent of the earliest thermal legislation. Many EU Directives and Regulations contain provisions on energy savings and efficiency, GHG emissions and environmental protection. Spain is faced with the difficult task of rehabilitating housing built before 1979 to comply with those requirements. The opaque building envelopes of a large sample of multifamily housing developments have been characterised as part of the REFAVIV research project. Four of these dwellings were monitored for over 30 months. The present paper analyses indoor comfort in these homes to better understand their energy balance and propose the most fitting rehabilitation measures.

**Keywords:** Social housing, energy rehabilitation, envelope, passive strategies, Madrid

### Introduction

The construction systems and opaque envelopes on a large sample of multi-family social housing complexes in Madrid and Seville, Spain, have been characterised as part of the 'REFAVIV' research project (Alonso et al., 2016) (Domínguez et al., 2016). As these buildings were erected before the 1979 enactment of the country's earliest thermal requirements for buildings (RD. 2429. NBE-CT 79), comfort and energy efficiency are sub-standard in most. Some of their lower-income occupants experience energy poverty. In 2001, 68 % of the primary housing in Madrid had been built between 1940 and 1980 and nearly 29 % had been erected in the nineteen sixties (Oteiza et al., 2016). Although located at the time on the outskirts of the city, those buildings now lie within the urban core (Martín-Consuegra et al., 2016).

The indoor environment in a few units was monitored to analyse the comfort afforded and propose future rehabilitation for improvement. Indoor temperature and humidity were logged for over 30 months in 2014, 2015 and 2016.

This article analyses the indoor comfort prevailing in a small sample of four units in different housing complexes in Madrid built in the nineteen fifties and sixties. The aim is to gain a fuller understanding of their energy balance to propose the most fitting rehabilitation

measures, on the premise that passive strategies are the most effective for attaining the objectives of energy efficiency and thermal well-being.

### Description of the four case studies

The four units analysed are located in different social or subsidised housing projects in Madrid. All were built prior to 1979 with fired clay brick envelopes but different wall thicknesses. One (dwelling 4) had an air space and none thermal insulation (Table 1).

Madrid, which lies at an altitude of 650 M, has a Mediterranean continental climate. According to meteorological records (AEMET, 2017), the years analysed, 2014-2015-2016, were extremely warm. The high temperature in 2014 was 37.3°C (17 July), the mean 16.1°C and the low -1.9°C (30 December). In 2015 the high was 39.6°C (6 July), the mean 16.6 °C and the low -1.7°C (8 February). In 2016 the high was 38.9°C (6 September), the mean 16.0°C and the low --2.5°C (17 February).

In the summer of 2014 the mean high in July was 37.3°C, with a mean temperature for the month of 24.9 °C. In 2015 the mean high was 36.6°C, with a mean temperature in July of 29.8 °C. In 2016 the mean high was 35.1 °C, with a mean temperature in July of 28.1°C.

The mean low temperature in 2014 was 11.1°C , in 2015 11.3°C and in 2016 11.0°C. Humidity is generally low in Madrid's dry climate which, together with its altitude, translates into substantially lower night time than daytime summer temperatures. In December 2015 the mean relative humidity was 73 %, compared to a mean of 37 % in July.

Table 1, on next page, lists some of the characteristics of the four units that may affect indoor environmental conditions, including building typology, orientation, storey, net floor area, occupants (number), construction characteristics of the opaque envelope, wall thickness, catalogue transmittance of the wall materials (U-value in W/m<sup>2</sup>K), type of windows, window transmittance, solar protection and heating and cooling facilities.

### Data collection

The four dwellings were monitored for temperature (T) and relative humidity (RH) for over 2 years with the instruments described below. These data were then related to the dwelling characteristics.

#### *Thermohygrometers*

A Lascar EL-USB-2-LCD thermohygrometer was installed in the living area of each dwelling at an approximate height of 1.5 m to log temperature (T) and relative humidity (RH) every 30 min for over 30 months (June 2014 to December 2016).

Digital thermohygrometer specifications: T range, -35°C-80°C; internal resolution, 0.5°C. RH range, 0 %-100 %; internal resolution, 0.5 %.

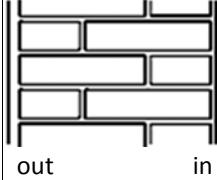
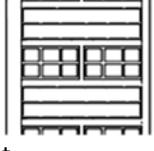
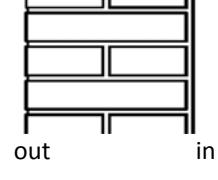
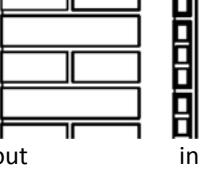
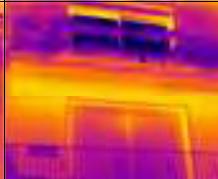
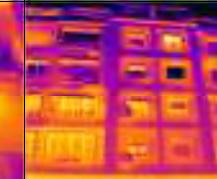
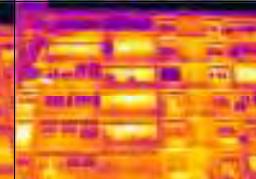


Figure 1- T and RH data logger

#### *Thermographic imaging*

A FLIR B335 thermographic camera was used to take thermographic images of the four dwellings in February 2016 (images in Table 1).

Table 1- Thermal characteristics of the units

Dwelling	1	2	3	4
Year built	1953	1960	1955	1962
Urban typology 				
Photos: Google maps	closed compound	open periphery	city block	open compound
Storey	3 of 5	4 of 4	4 of 7	4 of 8
Net floor area( $m^2$ )	77	60	80	84,5
Clearance (H) (m)	2,70	2,70	2,70	2,60
Occupants (No.)	4	2	1	4
Envelope ( $m^2$ )	44.81	71 + 60 (roof)	42	49
Volume ( $m^3$ )	208	162	216	220
Form factor	4.64	1.24	5.14	4.49
Façade	 out      in	 out      in	 out      in	 out      in
Thickness (cm)	38	27	25	40
Thermography				
Area and orientation	N - S - E 23.48 $m^2$ W 21.33 $m^2$	N 20.20 $m^2$ S 22.50 $m^2$ E 12.28 $m^2$ W 8.91 $m^2$	N 13.74 $m^2$ S - E 14.61 $m^2$ W 4.87 $m^2$	N 16.85 $m^2$ S 14.65 $m^2$ E - W -
U-value (W/ $m^2K$ )	1.34 (PB)	1.25 (FB)	2.61(SB)	1.13 (PB)
Windows	Aluminium + double glazing	Aluminium with TB + low-E double glazing	Aluminium + double glazing	PVC + double glazing
Area and orientation	N - S - E -6 $m^2$ W -7 $m^2$	N -4.00 $m^2$ S -0.70 $m^2$ E -2.30 $m^2$ W -	N 3.00 $m^2$ S - E -4.56 $m^2$ W -1.21 $m^2$	N -6.55 $m^2$ S -10.60 $m^2$ E - W -
U-value (W/ $m^2K$ )	3.72	2.72	3.72	3.08
Outer solar protection	PVC blinds	None	PVC blinds Awning	PVC blinds Awning
Heating	Building-wide (distributor and thermostatic V.)	Private	Building-wide	Building-wide
Cooling	None	None	None	Stand-alone facility

PB: perforated brick; FB: 8 cm facing brick; SB: solid brick; TB: thermal break;

## Results

The graphs in Figures 2 and 3 show the T data collected in the four units in winter 2015 and summer 2014. The temperatures recorded were often above (in summer) or below (in winter) the target values laid down in Spain's Technical Building Code (CTE BD HE, 2013) for housing, i.e., a maximum of 27°C in summer and a minimum of 17°C in winter. The comfort zone was defined as 20°C-25°C.

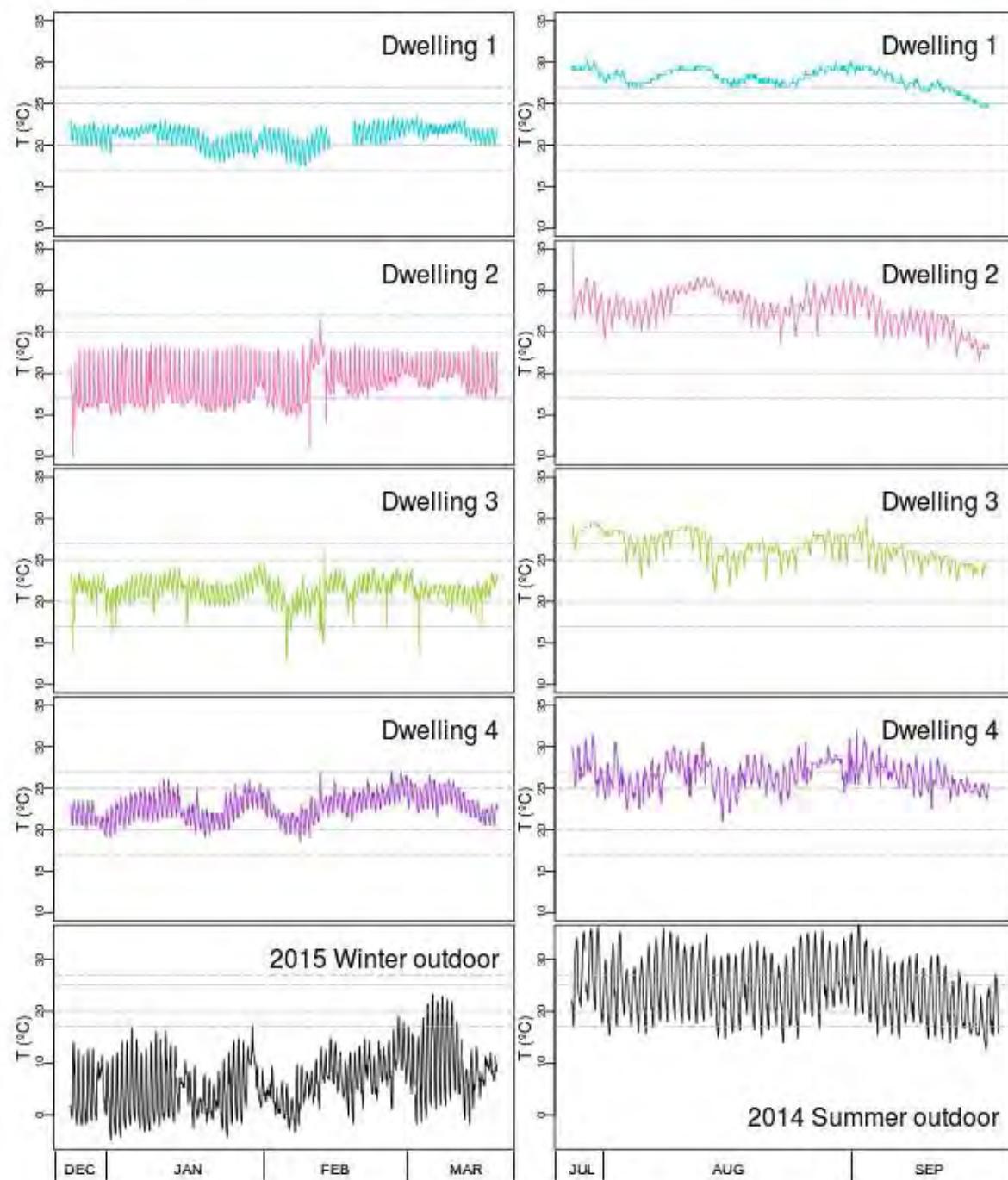


Figure 2. Winter temperatures, 2015

Figure 3. Summer temperatures, 2014

Figure 2 gives the indoor temperatures in the four units in winter 2015 as well as the outdoor temperatures in the same period. Note that whilst the indoor winter temperature in all the dwellings fluctuated primarily within the CTE target range (17°C-27°C), clear differences can be observed among them. Temperature fluctuated least in dwelling 1 and was also fairly steady for dwellings 3 and 4 with an occasional peak, although mainly within the comfort zone. Superheating (25°C-27°C) was observed at times in dwelling 4. The peaks and valleys (or rises and falls) in temperature were steeper in dwelling 2 than in the others and although the temperature ranged mostly from 17°C to 20°C, it dipped below 17°C on the coldest winter days. The outdoor temperature was below 17 °C during most of the winter (day and night), with higher values recorded only during a few weeks in March in the daytime.

As Figure 3 shows, in summer 2014 indoor temperatures above 27°C predominated in the four dwellings. As in winter, the values were most stable in dwelling 1, with no significant day/night fluctuations and with temperatures under 27°C only at the end of the season. The other three dwellings exhibited peaks during the day and (ventilation-mediated) valleys at night. The temperature was below 27°C on a substantial number of days in dwelling 3 as well as in dwelling 4, although as the latter had mechanical (AC) cooling, the lowest temperatures were recorded when the outdoor temperature was highest. Daily outdoor temperatures fluctuated widely from 37°C-40°C during the day and 20°C-23°C at night, whilst in September they remained within the target range: 27°C-17°C.

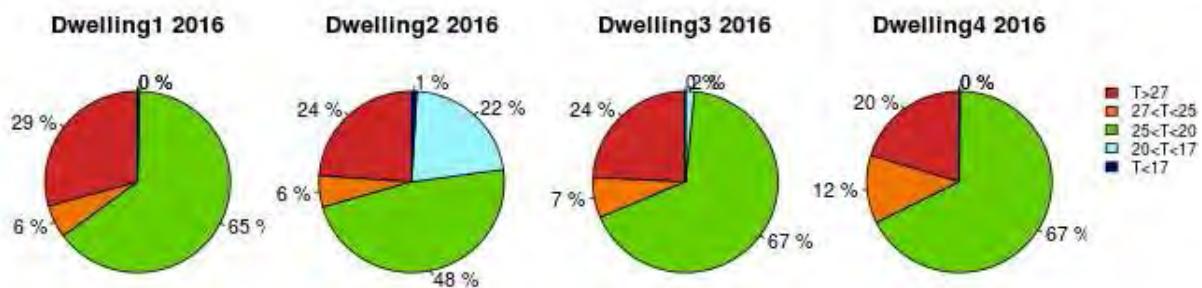


Figure 4. Yearly distribution (2016) of indoor temperature in four dwellings

The pie graphs in Figure 4 show the percentage of hours in 2016 (December 2015-December 2016) in which indoor temperatures lay within four ranges: purple indicates  $T < 17^\circ\text{C}$  (cold environment); blue,  $T = 17^\circ\text{C}-20^\circ\text{C}$  (cool but acceptable); green,  $T = 20^\circ\text{C}-25^\circ\text{C}$  (comfort zone); and orange  $T > 27^\circ\text{C}$  (warm environment). In dwelling 1, comfort zone temperatures were recorded 65 % of the time and in dwellings 2 and 3, 67%. In dwelling 2 the temperature was in the comfort zone 48 % of the time and 23 % of the time it was below 17°C. Temperatures of 27°C-25°C were recorded during 12 % of the time in dwelling 4, 7 % of the time in dwelling 3 and 6 % of the time in dwellings 1 and 2. The number of hours with  $T > 27^\circ\text{C}$  (warm environment) was similar, at around one-fourth of the time, in all four dwellings, ranging from 20 % in dwelling 4 to 29 % in dwelling 1.

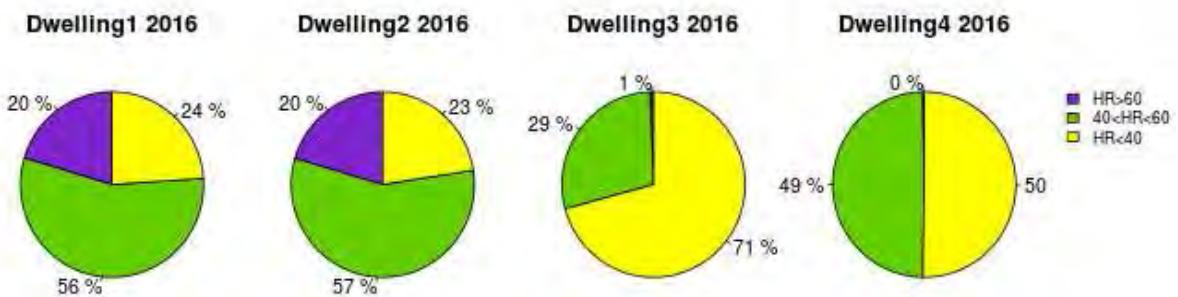


Figure 5. Yearly distribution of relative humidity in four dwellings

The pie charts in Figure 5 show the percentage of hours in 2016 at which the indoor relative humidity in the four units was in one of three ranges: purple indicates RH>60 % (humid environment); green, RH=40 %-60 % (comfort zone); and yellow, RH<40 % (very dry environment). In dwellings 1 and 2 RH was in the comfort zone for 55 % and 56 % of the year, respectively, in dwelling 4 during 49 % and dwelling 3 during only 29 % of the total hours. In dwelling 3 RH was below 40 % (very dry environment) for 71 % of the time and in dwelling 4 for 50 % of the time, while dwellings 1 and 2 had a very dry environment for 24 % and 23 % of the hours, respectively. Relative humidity of over 60 % was recorded in more than 20 % of the total hours in dwellings 1 and 2 and less than 1 % of the time in dwellings 3 and 4.

## Discussion

This part is divided into the 4 most relevant aspects of the analysis.

### *Hygrothermal comfort*

The heating installed in the four units delivered indoor temperatures within an acceptable range (17°C-25°C) in the winter time. In the four, the temperature was above 27°C for 20%-29 % of the time (2016), all in the summer months. Summertime temperatures were over the acceptable 25°C-27°C range most of the time.

Dwellings 1 and 2 exhibited more hours of comfortable RH (40%-60%) than dwellings 3 and 4. This may be due to usage or in the case of dwelling 2 to its location, near a river and green belts. More hours with RH of below 40% were recorded for dwelling 3 than any of the others, due to its location in an urban area with a high building density, no green spaces and a very compact residential typology. Moreover, building-wide heating systems dry the indoor environment in the winter.

The differences found in the temperature and humidity ranges in the four units suggest the need to use an enthalpy indicator for more accurate energy balance calculations.

### *Heating*

Dwelling 2, for which the T graph exhibited the widest fluctuations, had a thermostat-adjustable private heating facility. The resulting indoor ceiling temperature obviated any wintertime superheating. In addition, the dwelling was in the comfort zone only when it was occupied. In the other units, located in buildings with a shared heating facility, it was more difficult to adjust the temperature to comfort levels. The temperature rose above 25 °C any number of times during the winter. Of the units with building-wide heating, only dwelling 1

was fitted with thermostatic valves in each radiator and meters to record consumption by each unit, arrangements that incentivised greater control over the indoor temperature.

### **Cooling**

Temperature in the four units lay outside the comfort range most often in the summer, with temperatures higher than the 27°C target despite the solar protection systems in dwellings 3 and 4. Only dwelling 4 used a mechanical AC system on occasion.

### **Envelope**

Dwelling 1 had more uniform thermal behaviour in winter and summer both, very likely because the greater thermal mass afforded by its thicker envelope attenuated outdoor cold/heat waves. One of the reasons for the temperature fluctuations in dwelling 2, in addition to the lack of insulation, could be that as the highest storey in the building, it had a larger area in contact with the outdoors, with an envelope including both façade and roof.

Variations in humidity were related to envelope water-tightness, among others.

## **Conclusions**

As the units studied were heated, thermal comfort was greater in the winter than in the summer, although to the detriment of the environment.

In Madrid's Mediterranean continental climate, indoor comfort can be improved by using passive measures, thereby reducing energy demands. The quality of the buildings' construction is well below the current standards. Energy consumption could be reduced, ameliorating the level of comfort by improving its thermal performance.

The use of passive measures during summer is a common practice (awnings, blinds, night time ventilation) and internalised by users. In the winter, however, occupants rely on heating to ensure comfort. It is foreseeable that the lack of comfort during summer (Fig.4), in addition to the expected climate change, will increase consumption due to the installation of cooling equipment.

The low levels of humidity in these units makes evaporative cooling a good passive option to lower the summertime temperature. The energy used in the winter dries the environment. Such substantial alterations in HR levels support the argument for using an enthalpy indicator for energy characterisation.

## **Acknowledgements**

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## **References**

- Agencia Estatal de Meteorología, AEMET. Opendata. 2017
- Alonso, C.; Oteiza, I.; García-Navarro, J. and Martín-Consuegra, F. (2016). 'Energy Consumption to Cool and Heat Experimental Modules for the Energy Refurbishment of Façades. Three Case Studies in Madrid'. *Energy and Buildings* 126: 252–62. doi:10.1016/j.enbuild.2016.04.034.
- Código Técnico de la Edificación (CTE). CTE BD HE, 2013 <http://www.codigotecnico.org/> (Accessed 29/03/2017).

Domínguez, S.; Sendra, J.J.; Oteiza, I. (2016) *La envolvente térmica de la vivienda social: el caso de Sevilla, 1939 a 1979*. Monografías Editorial CSIC. Madrid- Spain.

Martín-Consuegra, F.; Hernández Aja, A.; Oteiza, I.; Alonso, C. (2016) Energy needs and vulnerability estimation at an urban scale for residential neighbourhoods heating in Madrid (Spain). *PLEA 2016*. Los Angeles. USA.

Oteiza, I.; Alonso, c.; Martín-Consuegra, F.; Monjo J. and González-Moya, M. (2015). *Energy Retrofitting for Social Housing by Improving the Building Envelope: Madrid, 1939-1979*. <http://ebooks.benthamscience.com/book/9781681080642/chapter/131498/>

RD.2429. NBE-CT-79, (1979). "Real Decreto 2429/1979, de 6 de julio, por el que se aprueba la norma básica de edificación NBE-CT-79, sobre condiciones térmicas en los edificios". Presidencia del Gobierno, Spain.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Retrofit Strategies for the Existing Residential Tower Blocks in Northern Cyprus

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**Abstract:** This paper presents a study to investigate the actual building energy use and measures to improve the energy efficiency of residential tower blocks in the Turkish Republic of Northern Cyprus (TRNC). One of the main concerns is that, the TRNC is burdened with the legacy of poorly built housing stock accumulating over the last few decades. There are no strict measures or benchmarks for building energy performance, nor an official roadmap for regulating 'retrofit strategies' to improve energy efficiency. The aim of this study is to develop and test potential retrofit strategies aimed at optimising the energy performance of the existing residential tower blocks in the TRNC. This research adapts a quantitative research design primarily using computer software simulations in a case study approach. To capture the existing energy consumption, physical characteristics of selected case studies are incorporated into the energy simulation analysis. In this case study approach, three prototype residential tower blocks are analysed related to occupants' energy use patterns. To accomplish this, the study first examines three prototypes of typical residential tower blocks built in the 1970's, 1990's and 2010's. The modelling software used is REVIT 2017 with 'Green Building Studio' as a plug-in for energy performance analysis and simulation. This paper reports on the preliminary simulation results that demonstrate that the 73% of the total heat loss from the buildings is due to air infiltration, un-insulated external walls, and windows (resulting in high annual energy demand for cooling), particularly in the south-east facing flats.

**Keywords:** Energy Efficiency, Energy Performance, Retrofit, Northern Cyprus

### Introduction

This research project is undertaken in Famagusta, Turkish Republic of Northern Cyprus (TRNC). Understanding the importance of energy performance of the existing building stock constitutes a thorough cultural and societal challenge. It plays a crucial role in the efforts to reduce the negative environmental impacts of inefficient construction activity. Energy and carbon reductions from the existing building stock take high priority in both, the construction and residential sectors (Salat, 2009). The main objectives for energy saving targets are cost savings and reduction of carbon-dioxide emissions. However, in the TRNC, two critical features of the housing sector are the absence of regulatory bodies to oversee the process of construction and the fact that the majority of housing stock is poorly built by privately owned construction companies (Yapicioglu and Wright, 2014). Hence, without institutional structures within the country to oversee building initiatives, it becomes almost impossible to bring the building sector into European Union standards (Ulucay, 2008). The study aims to investigate the current energy consumption patterns (heating and cooling

demand) of three different prototypes of existing residential tower blocks (RTBs) and explore the potential energy saving outcomes of implementing energy efficient technologies in retrofit strategies. The study also intends to propose cost-effective retrofit strategies that would bring about significant energy savings and carbon reductions to the residential sector in TRNC. The main question is: What are the feasible and efficient retrofit strategies for upgrading energy performance of three sample prototypes of RTBs?

In this study, adoption of cost-effective retrofit strategies has extended to take into account and demonstrate how the location of buildings and the type of construction materials become vital components in energy consumption supported with the critical insights of occupants' energy use variation. For this research, initially, three residential tower blocks were investigated and evaluated in terms of their orientation, floor plan designs, building age and materiality. Then, three high potential of deep retrofit strategies were selected and then evaluated in detail via employing energy analysis simulation packages.

Architectural prototypes of three distinct construction periods and technologies of existing RTBs are modelled using REVIT 2017 with a supporting plug-in 'Green Building Studio' energy simulation software package. The main variables focused on as having major impact on heating and cooling demand are: the demographic structure of households, plan organization of the building, and the construction materials. Results are obtained for each retrofitting schemes' feasibility by analyzing in energy use intensity and life cycle energy use. This paper presents and discusses the initial findings of the residential tower block 3 (RTB3) in order to respond to the scope of the research.

### **Background - Location and Climate**

According to the Koppen-Geiger climate classification, Cyprus has climate characteristics that are typical Mediterranean. The Koppen-Geiger climate data shows that the overall climate of Cyprus is a Subtropical (Csa) type climate and partly Semi-Arid (Bsh) type climate in the north-eastern part of the island (Kottek, 2006). That is to say, the climate characteristics of Cyprus are hot and dry during summertime (see Figure 1).

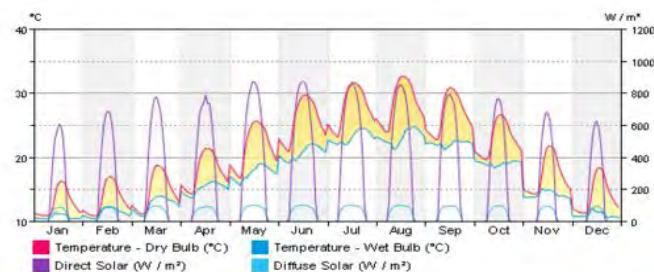


Figure 1: Diurnal weather averages of the research context.

Source: Autodesk - REVIT2017 'Green Building Studio' energy analysis report - weather data, (2017).

The climate of Famagusta, the location of the study, shows mild characteristics of Mediterranean climate (The Cyprus Meteorological Service, 2013). Maximum Dry Bulb Temperature (DBT) may reach up to 42 Celsius in summer, which occurs in August and minimum DBT may drop down to -6 Celsius in winter that happens in January. Mean Minimum DBT changes between 6.8 Celsius and 22.3 Celsius while Mean Maximum (Hadjinicolaou, 2010). DBT varies between 16.3 Celsius and 33.3 Celsius. The prevailing winds come from north-east but the most consistent directions for wind are south-west and west (*ibid*). Hence, the hot and dry summers and wet moderate winters are the main

climate characteristics and have direct impact on the demands of annual heating and cooling demand, due to the requirement for summer cooling as well as winter heating.

## Methodology

The study adopts a ‘quantitative’ research design primarily using computer software simulations for future energy performance predictions. The study focuses on a case study approach in order to carry out analysis on three of the most common residential tower blocks prototypes in three different regions of Famagusta; including no man’s land of ‘Varosha’ territory, the ecological land of the city centre, and the urban agglomeration area. This approach helps provide a good representation of the common drivers in the property market with different levels of retrofit strategies and representative samples from three main construction periods of the 1970’s (RTB1), 1990’s (RTB2) and 2010’s (RTB3). These three different RTBs correspond to three different construction phases with respect to type, age, design and materials. The RTBs are chosen from privately owned construction companies specialised in mass housing development projects (mainly owner-occupied dwellings). For the buildings built in three distinct periods, these are described by three new variables defined to include energy consumption patterns of occupants, thermal performance of buildings and thermal comfort level of occupants. The input parameters required for the modelling include the building geometry and properties of the construction materials, specifications of the building components and the outdoor air temperature of the built environment, and occupants energy consumption. The periods of construction are determined by building techniques influenced by the building regulations of each phase; the choice of materials for windows, roofs, walls and other building elements. Energy simulations of the thermal performance of the buildings are conducted using meteorological data of a typical year in Famagusta. The building geometry was created for its initial existing state, every floor and apartment with correspondent thermal zones and subdivisions (see Figure 2 a,b,c&d), indicating clearly which zones and spaces are not heated like balconies, and storage areas.

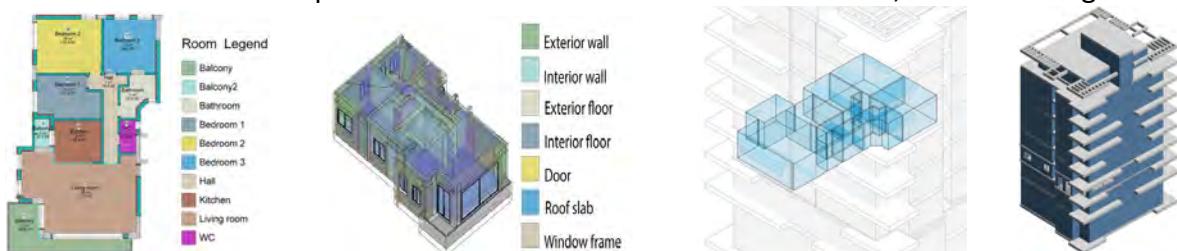


Figure 2 a,b,c&d: Floor plan organisation and the analytical energy simulation model of the tested apartment unit. Source: Autodesk - REVIT2017 ‘Green Building Studio’ energy analysis result, (2017).

Thermal specifications of construction materials are made according to the benchmarks of the British Construction Codes and Practices – Law 1959, which is the most recent data set available at the time of undertaking the research for this study.

Table 1: Thermal transmittance values of the external walls of the RTB3.

cast-in-situ concrete large panel wall	$U= 0.8-1.2W/(m^2K)$
brick wall (without insulation)	$U= 1.6-2.0W/(m^2K)$
autoclaved aerated concrete large block wall	$U=0.8-1.2W/(m^2K)$
aluminium framed single/double glazed windows,(without insulation) with a tow had	$U=2.5-3.0w/(m^2K)$

Source: State Planning Organisation of the TRNC, Building Construction and Parcel Statistics, (2010).

### **Case Study Building - RTB 3 - Alasya Park Apartments - 2010's residential tower blocks**

The estate was designed in 2010 and completed in 2013 (see Figure 3 a,b&c). It is fully managed by privately owned construction company and all flats are ultra-modern when constructed, having lifts, central heating and double glazed windows. It comprises 245 flats over seven 13 storey towers. In this case study building, many changes have occurred including measures carried out by households such as enclosures of balconies: adapting a storage/garage on the ground floor for residential use; extension to the penthouse apartments; where householders were not concerned about the thermal impact of increasing the window to wall ratio of their apartments. Approximately 90% of balconies are glazed or covered by different materials for shading purposes and there are too many external units for air-conditioning systems.



Figure 3 a,b&c: The Alasya Park - large scale en-mass housing estate, the modelled and simulated sample residential tower block.

Source: Image a&b - credits: Author, (2015) - Image: Revit 2017 'Green Building Studio', (2017).

### **Results and analysis: Retrofitting Advantages - Energy Performance of Prototype Building**

In this section, the residential tower block prototype RTB3 is modelled according to building geometry, floor plan organisation, construction material and orientation (south-east) of buildings. In that sense there is communication and collaboration between research, design, and the implementation of energy efficiency retrofitting and challenges come through the building energy performance simulation. For the retrofit strategies, the concepts were modified to ASHRAE 90.1-2010 retrofit package. The materials were selected to meet the U-value and other requirements defined in Table 1. By the performed Building Performance Systems (BPS) dynamic simulations/investigation and optimisation of different building envelope structures, it has been demonstrated that it is possible to significantly reduce heating and cooling loads. Table 2 demonstrates the contextual features of prototype building before retrofitting.

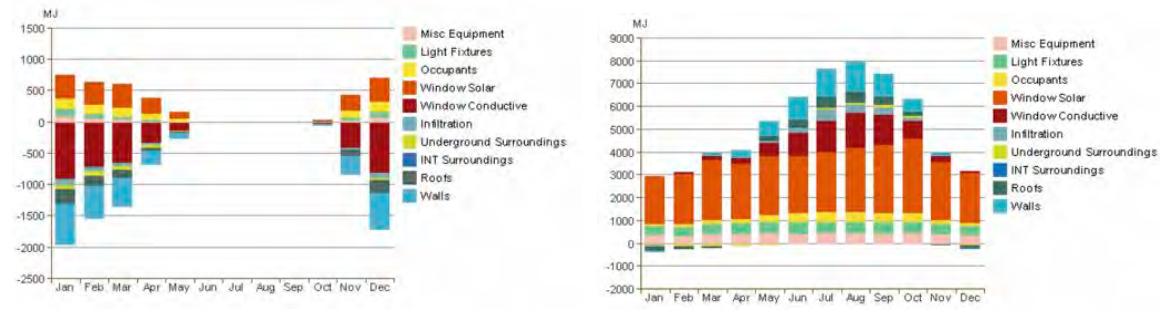
Table 2: The contextual features and simulation benchmarks of prototype building.

#### **Building Performance Factors**

Location:	35.1504554748535,33.908374786377
Weather Station:	1253615
Outdoor Temperature:	Max: 35°C/Min: 5°C
Floor Area:	81 m <sup>2</sup>
Exterior Wall Area:	96 m <sup>2</sup>
Average Lighting Power:	6.46 W / m <sup>2</sup>
People:	2 people
Exterior Window Ratio:	0.24
Electrical Cost:	\$0.14 / kWh
Fuel Cost:	\$0.78 / Therm

Source: Autodesk - REVIT2017 'Green Building Studio' energy analysis result, (2017).

The simulation results of the base case scenario for RTB3 building demonstrated that the 73% of the heat losses come from air infiltration, mainly through exterior walls without insulation, and windows (provoking a high annual energy demand for heating). The results of simulations performed for the upgraded models are shown in Figures 4 a&b. In terms of savings in specific heat losses, the exterior walls without insulation achieved 52% over the existing state, and the windows achieved 44%. This trend was followed by the roofs, the simulation measures have shown that the RTB3 achieved 41% of energy consumption reduction after retrofitting.



Figures 4 a&b: The monthly heating and cooling load of the RTB3.

Source: Autodesk - REVIT2017 'Green Building Studio' energy analysis result, (2017).

The diagram in Figure 4a shows that the specific annual energy demand for heating in the RTB3 can be reduced by 52% by applying the layer of thermal exterior insulation to the building envelope (new U-value 0.14W/m<sup>2</sup>K) and changing the existing double pane windows to triple pane windows (the existing U-value 2.10W/m<sup>2</sup>K), and further improvements led to a reduction of 73%, while in upgrading the windows (new U-value 0.7/m<sup>2</sup>k) in the RTB3, specific annual energy demand for heating can be reduced by 57% only by treating the building envelope, while the application of other measures such as energy efficient lighting use can provide a further 59% savings in the RTB3.

Figure 4b shows that a 30% reduction of cooling load for RTB3 is achievable by improving the building envelope (new U-value 0.15W/m<sup>2</sup>K), by placing new exterior thermal insulation. Cooling design calculations are carried out to determine the capacity of mechanical cooling equipment required to meet the hottest summer design weather conditions and this was determined as parameters of energy measures during the simulation processes. By further increment of the insulation thickness, a significant decrease in cooling load can be noted for both south-west and south-east facing spaces. It is also remarkable to note that placing a well-ventilated facade achieved significant energy savings for cooling, up to 35% in upgrading envelope of the exterior wall. A similar scenario also can be seen in upgrading insulation of the roof, where there is a slight noticeable increase in cooling design capacity for upgrading U-values of windows, but by installing a ventilated facade savings up to 34% are achievable in the RTB3.

### Discussions: Potential energy retrofit scenarios

The building envelope is an important component in the building structure as the interface between the interior of the building and the outdoor environment. Kylili and Fokaides (2015) assert that a feasible solution for achieving energy savings in existing buildings through interfering with the building construction is upgrading exterior wall systems. Besides building physics, energy conscious retrofit scenarios have considered the architectural measures that affect the overall improvement of the actual energy

performance of buildings. The presented scenarios are studied globally, apart from sustainable Energy Efficiency Implementation (EEI) measures and local construction practices, and have given models of improvement suitable for this research context. Table 3 shows the typical assumptions of energy consumption and carbon emissions of the 'building form' energy performance measures during pre and post retrofit phases.

Table 3: The energy consumption reduction measures during the pre and post retrofitting.

<b>1 Base Run</b>	<b>2 Design Alternative</b>
<b>Energy, Carbon &amp; Cost Summary</b>	<b>Estimated Energy &amp; Cost Summary</b>
Annual Energy Cost <b>\$2.274</b>	Annual Energy Cost <b>\$1.683</b>
Lifecycle Cost <b>\$30.967</b>	Lifecycle Cost <b>\$22.919</b>
<b>Annual Energy</b>	<b>Annual Energy</b>
Energy Use Intensity (EUI) <b>674MJ/m<sup>2</sup>/year</b>	Energy Use Intensity (EUI) <b>674MJ/m<sup>2</sup>/year</b>
Electric <b>15.414 kWh</b>	Electric <b>11.349 kWh</b>
Fuel <b>5.209 MJ</b>	Fuel <b>4.966 MJ</b>
Annual Peak Demand <b>5.3 kW</b>	Annual Peak Demand <b>3.6 kW</b>
<b>Lifecycle Energy</b>	<b>Lifecycle Energy</b>
Electric <b>462.413 kW</b>	Electric <b>340.477 kW</b>
Fuel <b>156.054 MJ</b>	Fuel <b>149.870 MJ</b>

Source: Autodesk - REVIT2017 'Green Building Studio' energy analysis result, (2017).

The proposed solution for energy consumption reduction of the building is installing thermal insulation terracotta ceramic tile (new U-value 0.14W/M2K), replacement of windows and door glazing (from single to double or triple, low-e glazing), and wood-framed door/window openings that led to a considerable reduction in the heat losses through building envelope. The thickness of additional insulation for the facade and floor ( $U=0.04W/(m^2K)$ ) was 100, 200, 300mm, for the roof the change of original 175mm insulation and additional insulation of 50, 150, 250mm, which can reduce the amount of heat that the building absorbs due to partial reflection of solar radiation. (Green Building Studio, 2017).

Three energy saving measures were considered from the upgrading of existing windows ( $U$  1.5W/(m<sup>2</sup>K)) to the installation of double glazed windows ( $U$  1.2 and 0.7W(m<sup>2</sup>K)). Two different new door options also were considered ( $U$  1.5 and 1.0W/ (m<sup>2</sup>K)) (ibid). It is also noted that the base case is RTB3 with its proposed structure and service systems that provide indoor climate according to ASHRAE 90.1 N2010 standard (an acceptable, moderate level of expectation). Along with improved energy efficiency, also indoor climate was upgraded to correspond to ASHRAE benchmark (normal level of expectation) requirements. Additionally, mechanical supply and exhaust ventilation with two types of ventilation heat recovery efficiency was considered: 60% and 80% in the RTB3.

One essential element in the strategies proposed was the glazed enclosure of the balconies, which caused an aesthetic change of appearance of the building envelope, by means of sliding glass elements, which created a thermal buffer zone in the winter. Glazed enclosure of the balconies is proposed in the RTB3, it is evident that the greater effect on reducing the

need for heating was achieved by upgrading building envelope, from 53% to 73% savings in order to exterior wall orientation and thickness of insulation materials. At the same time, in the summer time, intensive ventilation is required to prevent the glazed terraces from generating additional heat load. This is partly due to the current natural ventilation systems are not regulated and apartments are mostly under ventilated. Ensuring that ventilation airflows meet indoor climate standard requirements increases global costs, but energy savings cannot be achieved through lower indoor air quality as indoor air pollutants affect resident's health (Jones, 1999). For this reason, a ventilated facade was proposed, which can reduce the amount of heat that the building absorbs due to partial reflection of solar radiation by the covering and the ventilated air gap. It is also remarkable to note that the discount rate is a key variable for the life-cycle cost assessment calculation (LCA). The prices for the energy cost are chosen by the publication of the energy agency in Cyprus (Cyprus Energy Agency, 2015). Table 4 shows the life-cycle parameters of the calibrated case study building. Therefore, the overall energy use saving and life cycle energy use of retrofitting strategies are given in Table 5 (The costs have been calculated as the arithmetic mean of quotes independently by 'Green Building Studio' life cycle assessment plug in adds that indicating benchmarks in building retrofit.)

Table 4: The life-cycle parameters.

Parameter	Value	Unit	Reference Scenarios
Time frame	30	y	Kylili (2016)
Discount rate	3.5	%	Chrysostomou (2015)
<b>Price increase</b>			
Energy cost	3.32	%	Kylili (2015)
Building services	1.46	%	Avgelis (2009)

Table 5: Energy use intensity and life cycle energy use/cost of the RTB3.

Energy Use Intensity		Life Cycle Energy Use/Cost	
Electricity EUI:	<b>140 kWh/sm/yr</b>	Life Cycle Electricity Use:	<b>330.570 kWh</b>
Fuel EUI:	<b>206 MJ/sm/yr</b>	Life Cycle Fuel Use:	<b>484.600 MJ</b>
Total EUI:	<b>710 MJ/sm/yr</b>	Life Cycle Energy Cost:	<b>\$23.396</b>

Source: Autodesk - REVIT2017 'Green Building Studio' energy analysis result, (2017).

The investigation on the basis of prototype RTB3 shows that with the conditions of parameters of the calculation, the energy use intensity of heating and cooling demand in relation to the cost optimum is about 330.570 kWh/M2 per year. The analysis pointed out that the RTBs older than 30 years are profitable for retrofitting because of their low energetic quality. Because of the high effect on the building envelope materials, which requires the feasibility of the energy conscious retrofitting measures, the input parameters (benchmarks), such as the life-cycle parameters, including the discount rate of the energy price inflation, should be planned carefully.

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Green Building Studio. (2017). Energy performance analysis software package of REVIT 2017 plug-in adds.

Hadjinicolaou P, Giannakopoulos C, Zerefos C, Lange MA, Pashiardis S, Lelieveld J. (2010). Mid-21<sup>st</sup> century climate and weather extremes in Cyprus as projected by six regional climate models. *Reg Environ Change*, 1-17, <http://dx.doi.org/10.1007/s10113-010-0153-1>.

Jones, A. P. (1999). Indoor air quality and health. *Amos. Environ.* 33, 4535-4564.

Kottek, M., Greieser, J., Beck, C., Rudolf, B. & Rubel, F. (2006). World Map of the Köppen Geiger climate classification updated. *Meteorology.Z.*, 15, 259-263. DOI: 10.1127/0941-2948/2006/0130.

Kylili, A., Fokaides, P.A. (2015). Numerical simulation of phase change materials for building applications: a review. *Adv.Build.Energy Res.* <http://dx.doi.org/10.1080/17512549.2015.1116465>.

Kylili, A., Fokaides, P.A. (2016). Life cycle assessment (LCA) of phase change materials (PCMs) for building applications: a review. *J. Build. Eng.*

Papadopoulos, A.M., Oxizidis, S., Papanirtsas, G. (2008). Energy, economic and environmental performance of heating systems in Greek buildings. *Energy Build.* 40 (3), 224-230.

Salat, S. (2009). Energy loads, carbon-dioxide emissions and building stocks: Morphologies, typologies, energy systems and behaviour. *Building Research and Information*, 37, 598-609.

Ulucay, P. (2013). A Critical Evaluation of the Town Planning Law of Northern Cyprus in line with the European Spatial Development Perspective, Unpublished PhD Thesis, Eastern Mediterranean University, Famagusta, TRNC.

Yapicioglu, B. & Wright, L. (2014). Small but Complex: The Construction Industry in North Cyprus. School of MACE, the University of Manchester, Manchester, UK. 27th IPMA World Congress.

Yorucu, V. & Keles, R. (2007). The Construction Boom and Environmental Protection in Northern Cyprus as a Consequence of the Annan Plan. *Construction Management and Economics*, 25(1), pp:77-86.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Observation and analysis of passive solar home control strategies for active users

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**Abstract:** Net-zero energy homes in extreme climates of the North American Midwest require an optimized building enclosure, proper solar orientation and highly efficient renewable energy systems. Of additional importance are seasonal climate-based operation strategies. The Interlock House, built in 2009 for the US DOE Solar Decathlon, anticipates active user control. Climate extremes for this location range from hot and humid summers with 90°F/32 °C dry bulb and 74°F/23 °C wet bulb to very cold winters with -3°F/-19°C dry bulb. The design focused on current construction techniques and seasonal passive design strategies such as passive solar sunspace, thermal mass and natural ventilation in shoulder seasons. Efficient photovoltaic systems and evacuated solar thermal collectors meet energy demand effectively. An online interface and energy performance prediction suggested control strategies and schedules for relevant passive features anticipating daily weather conditions inform occupants about feasible control strategies for shading, windows, sunspace. This paper reports successful control operations, suggested set points and occupancy related challenges encountered during a full year of monitoring. Occupant –researcher interaction supported the fine-tuning of set points and control strategies, which will support future control strategies. Data analysis provides preliminary design and operation guidelines for future zero ready homes for this challenging climate.

**Keywords:** Net-zero energy, predictive control strategies, real time performance monitoring, passive solar

### Introduction

The Interlock House has been designed to achieve net-zero energy performance for the climate, one of the most extreme climates in North America with hot and humid summers and very cold winters, with design temperatures (dry bulb / wet bulb) ranging from 90°F/74°F (32.2 °C / 23.3 °C) in summer to -3°F (-19 °C) in winter. Transforming to accommodate the extremes of the seasons and interlocking with the outdoor environment, this house balances a reduction of energy consumption through design with solar thermal and electric energy production. An advanced sensor and data acquisition system has been installed to monitor energy production and consumption, to validate the design prediction and to investigate the impact of human behaviour on the interaction of production and consumption. Occupying a passive solar home provides an intimate connection with the climate conditions outdoors and requires active manipulation of shading and windows to achieve the stated goal to power the house solely with building integrated renewables over the course of one year (He, Passee, 2014).

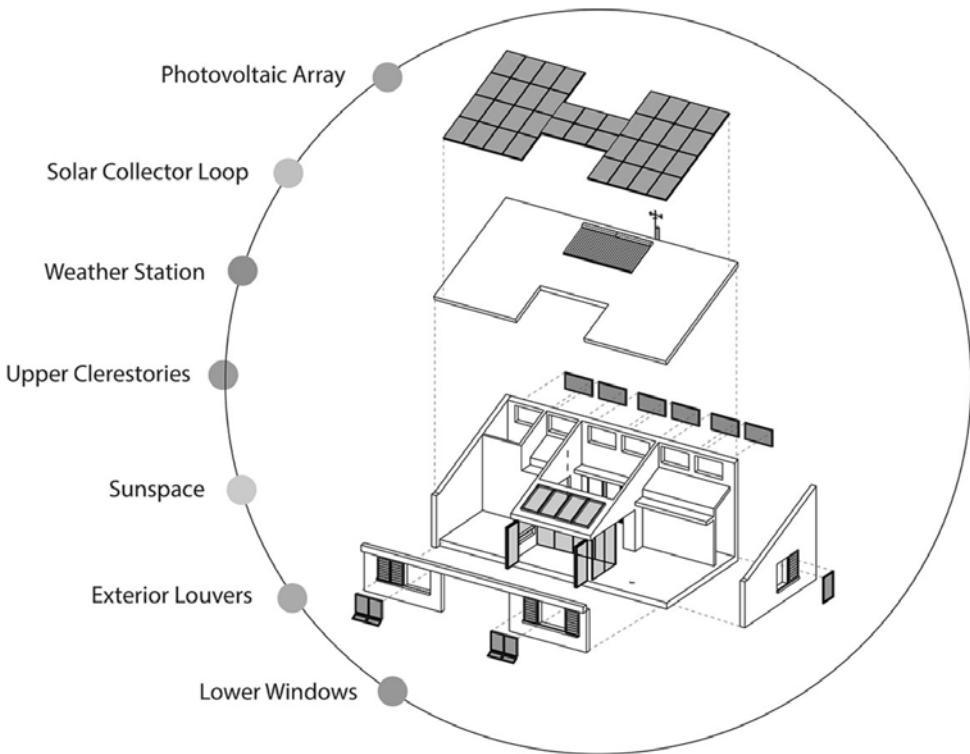


Figure 1: Interlock House: Sustainable design features

## Background

The 2009 US DOE Solar Decathlon challenged teams of university students to build a solar powered home and to operate it with a net-zero energy performance during a week-long period of measurement. In addition, simulations presented a net-zero energy balance for a representative year in the climate of the building's home location. Achieving net-zero requires both decreasing the energy consumption by improving the energy efficiency and increasing the energy supply from sustainable sources. In the investigated case, the energy efficiency was improved by integrating passive and active design features (see Figure 1). The design strategy was successful during the competition period in the relatively mild climate in Washington D.C. during three weeks of October of 2009 (Passe et al, 2016). To examine the potential energy performance of this house for the more extreme Midwestern climate with cold winter and hot summer, the house was monitored with a state-of-art data acquisition system (DAS) after relocation. With both sensor measurement and activity log, the project provides a thorough analysis of the post-occupancy energy performance.

Occupant behaviour is a major driver for building energy consumption and thus research needs to go beyond the design and performance simulation to studying occupant behaviour and control strategies. For example Hong and Lin 2013 simulated energy impact of how occupants set comfort criteria (including thermal, visual, and acoustic), interact with building energy and services systems, and studied how occupant response to environmental discomfort directly affect the operation of buildings and thus their energy use. They developed behaviour categories for three workstyles: 1) austerity – occupants are proactive in saving energy and manipulate set points after their arrival and ahead of their departure, 2) standard – average occupants manipulate set points only for times, when they are not present

and 3) wasteful – occupants do not care about energy use and never roll back temperature set points. Most buildings are operated to satisfy the ‘standard’ occupant, while the austere occupant might be needed to operate a net-zero building, as the paper will show. While it has to be noted, the building was not occupied at night and follow a very specific work day schedule, the presented data was collected to test standard occupant behaviour for a net-zero energy home.

## DESIGN CONCEPTS OF PASSIVE AND ACTIVE INTEGRATION

The integration of passive and active systems demands a complex interaction of spatial composition, building fabric and thermal and climatic conditions. This complexity is manifested in the open floor plan that uses convection to distribute passive solar heat gained from south-facing windows and natural ventilation for cooling and indoor air quality. The house sun porch extended this concept to transient zones, where space and envelope interact.

### ***Passive Design Strategy***

The spatial composition of the Interlock House is seasonal (see Figure 2). Thus, the Hall and Sun Porch can be reconfigured and opened to the environment. The Sun Porch (sunspace), with added thermal mass in the floor, mediates light and heat and encourages convective loops to heat and cool the house. A louver system spanning the south façade also mediates light and heat and reduces the active cooling load in summer. The house requires active manipulation of its doors, windows and exterior louvers to influence airflow and to maximize heat gain and loss. This reliance on several basic passive solar and ventilation techniques helps reduce the energy loads for the active systems. However, the effective meshing of active and passive systems needs an alert and motivated resident (Passe, 2012).

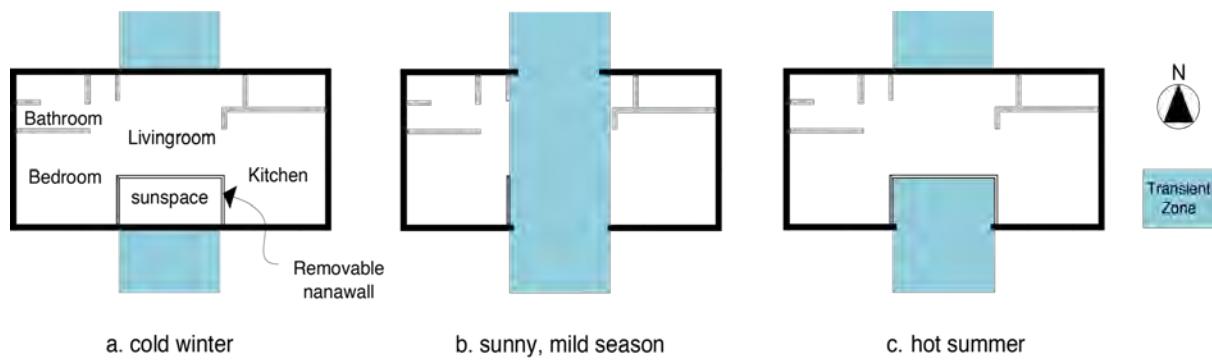


Figure 2: Interlock House: Seasonal operation strategies

The building envelope combines a tight, well-insulated wall system and well-positioned windows and door to facilitate passive solar and natural ventilation cooling. On the North, East and West, the house’s exterior wall construction includes a double cavity with an R value of 48 (8.45 metric), which is achieved with bio-based foam insulation in a two-by-six framing system twenty-four inches on center ( $5.08\text{ cm} \times 15.24\text{ cm} / 60.96\text{ cm}$  on center) with another one-and-one-half-inch (3.81 cm) additional layer of recycled blue jean insulation. The roof was installed with one layer of R-60 insulation (10.57 metric). Glass is minimized on the North, East and West elevation to prevent unwanted heat gains and losses. The fenestration patterns provide adequate day lighting throughout the year (Leysens et al, 2014) and are operable to admit fresh air and optimize passive ventilation by way of a through-section breezeway in the North-South orientation. (Passe et al, 2016; Jeanblanc et al, 2016). The southern side of this

breezeway employs two sliding glass walls that allow full opening for multiple seasonal responses, including a solar-collecting porch with glass, the outer layer of which admits maximum solar radiation in winter. The Northern side of the house incorporates Vacuum Insulated Panels into an operable system. Thermal mass was integrated into the building fabric wherever possible, for example in concrete countertops to serve as summer and winter diurnal energy storage.

### **Active Design Strategy**

The heating and cooling system of the house is based on maximizing year-round solar thermal collection. The concept enables heating and cooling powered fully or partially by solar thermal energy. A propylene glycol and water solution functions as the working fluid for thermal energy collection. The glycol solution is heated by a large bank of 60 Apricus evacuated tube collectors. These collectors are capable of heating the fluid to much higher temperatures than those attainable with flat plate collectors. The evacuated tubes are oriented to the south at the same 23° angle as the roof. The heated glycol solution passes through a heat exchanger that heats thermal storage water, which is stored in a large insulated tank. For winter heating, hot water circulates through a three-loop radiant floor heating system. A traditional vapour compression air conditioning system handles the sensible and latent cooling load. In addition to the radiant heating, electric cooling systems, an electrically powered energy recovery ventilator (ERV) provides fresh air to the interior space. The incoming air is conditioned to the same temperature and humidity as the air in the conditioned space using recovered heat and moisture from the outgoing airstream. Domestic hot water (DHW) is heated by a heat exchanger tied to the main thermal water storage tank. An electric resistance heater is integrated into the DHW tank as a backup heat source (see Figure 3). Electricity is generated by 38 205 Watt-rated photovoltaic panels and 2 DC to AC inverters.

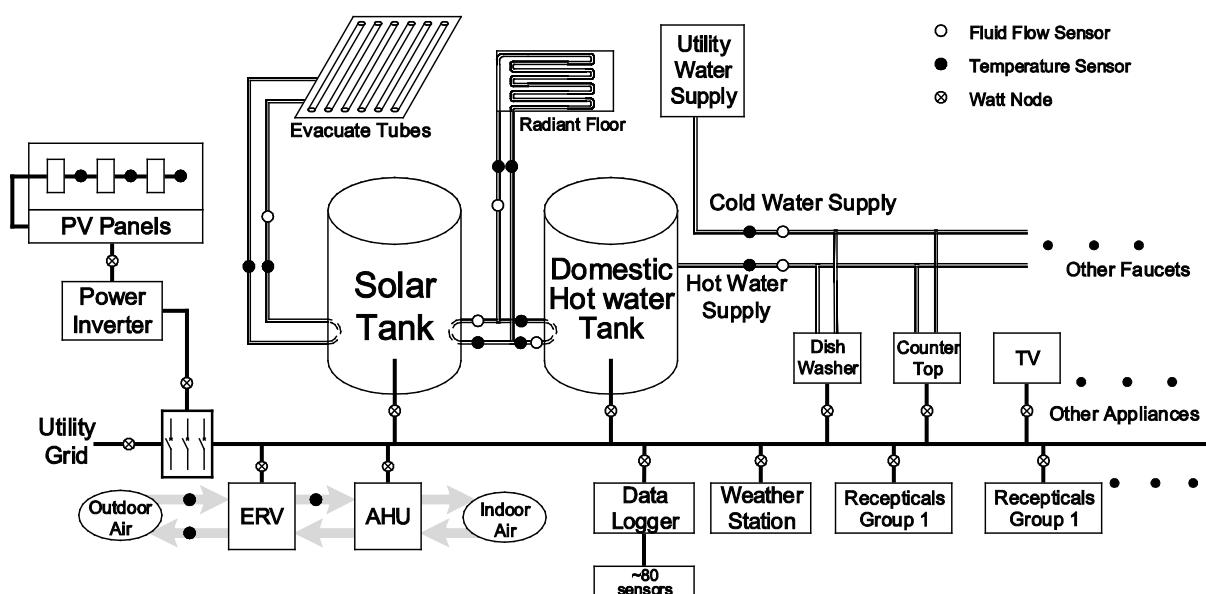


Figure 3: Interlock House mechanical system diagram

### **Performance monitoring to evaluate operation strategies for a net-zero energy balance**

After multiple years of testing, fine tuning and adjusting the house systems (He et al 2014), the 'official year of monitoring' lasted from June 16, 2015 to June 15, 2016. During this time,

the energy performance of the house was closely observed and summaries of the house energy performance discussed and made available to the occupants on a daily basis to support their building operation decisions. The data from the DAS was loaded for visualization purposes in a commercially available database (<https://eagle.io>). Publicly available weather forecasts (weather.com) provided suggestions for the next day building operation to fine tune operation strategies and set points and comfort perception of the occupants to balance their needs with energy performance: Net Energy to Grid (W), A/C Power and Heat usage, Outside/Main Floor Temperature, Relative Humidity, Cooling Set Point. The home produced more energy than it consumed from June 16<sup>th</sup> till November 15<sup>th</sup> with a net production of 2343.3 kWh, then it consumed more than it produced till March 5<sup>th</sup>, 2016. Then the house again produced more energy than it consumed. The last day of the official year of monitoring was June 15, 2016, a hot, sunny day, which brought good electrical energy production, but also high energy consumption. The indoor relative humidity was about 49-54%. The year ended with a 1047 kWh cumulative, net CONSUMPTION since June 16, 2016, thus not fully meeting the net-zero energy goal.

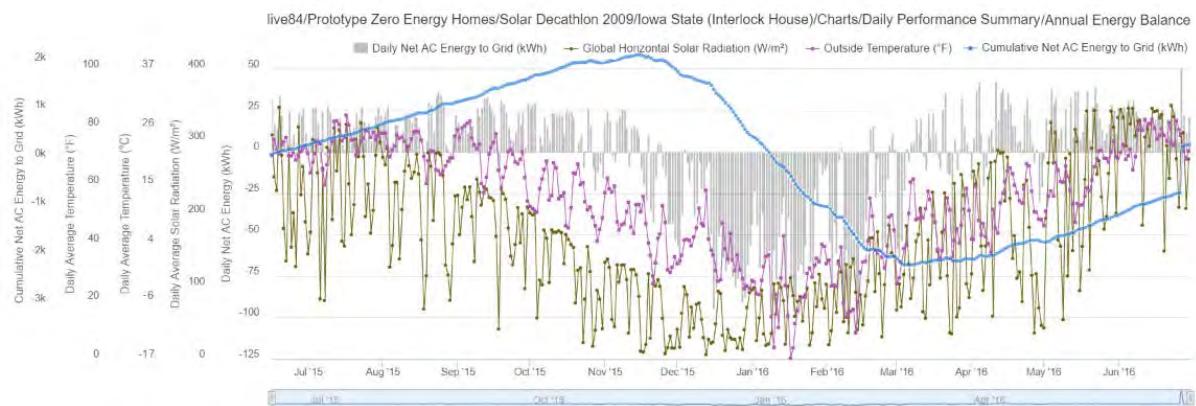


Figure 4: Annual net-zero energy performance versus climate (solar radiation and outdoor temperature)

## Occupant Behaviour and Building Control Strategies

While the house was designed for the active user, who would watch the weather and adjust the house features accordingly to keep a positive energy balance, this alertness is not often possible, if work occupant schedules are opposed to required operation schedules. Therefore, an internet-based interface provided the occupants basic control over heating and cooling set points and to encourage the use of passive strategies by introducing a “Windows and Doors Open Mode”. The purpose of the “Open Doors/Windows Mode” on the control interface is to disable the heating and cooling systems when doors/windows are open. This setting must be manually activated and deactivated by the occupants because the house was built without sensors on the doors and windows. Occupant work schedule was noted to enable suggestions for potential operation strategies and an ‘Unoccupied’ mode assigned. Occupants were able to adjust set points freely. The particular occupants felt uncomfortable if the temperature was less than 72 °F / 22 °C.

## Control and Operation Strategies and Winter Set Points

Over the course of the year, the occupants and researchers noticed, that the major challenge for reaching the net zero energy balance was the relationship between night time set point (Unoccupied mode), solar hot water storage capacity, backup electrical heating and start time

for occupied mode set point with respect to the warming up of the building through passive means. While the electric heating element would not turn on during the night when the heating set point for unoccupied mode was set back to 62 °F / 16.67 °C during milder seasons, it also did not take long to reach occupied mode temperature of 72 °F / 22 °C. On cold winter days, it would take three to four hours to heat the house back up from 62 °F / 16.67 °C to 72 °F / 22 °C after a cold night, which provided non-comfortable conditions for the occupants in the morning. Therefore, throughout the winter, the heating set point was left at 72 °F / 22 °C after this observation. Throughout the winter, the relationship between outside temperature and schedule for occupied set points provide very good opportunities to improve the performance of the building by refining the control/setback algorithm and taking advantage of predictive control based on upcoming weather conditions.

#### ***Seasonal challenges for solar hot water, domestic hot water tank and air conditioning use***

When either tank temperature drops below its set point, its backup electric heating element provides heat using electric energy and thus reducing the net zero energy balance. During local winters, the contribution of the solar thermal collector was minimal as the tank proved too small to store sufficient heat to keep the set points during long cold nights and the solar energy is not yet available at 8 am to warm up the tank to meet occupied set point. During the spring, summer, and fall, the contribution of the solar collector was very significant. The spring (March 21) and fall (Sept 21) equinoxes are the times of year when solar contributions changed most rapidly. Even on relatively mild nights, the indoor temperature remained a few degrees below 72 °F / 22 °C when occupants arrived in the morning unless the heat turned on overnight. Unfortunately because the building starts the day at 72 °F / 22 °C, it tends to overheat on sunny days in the afternoon even in winter, because the heat turns on for several hours in the early morning so that it is 72 °F / 22 °C. Then the building overheats a couple hours after they arrive. In the extreme case, the building uses excess energy to heat back up from the setback temperature to 72 °F / 22 °C, but all that heat is only beneficial for a first couple of hours on sunny days before overheating becomes a problem. Data showed that even on mild days the heat briefly turned on in the morning using the radiant floor heat at about 9 am, which was an hour after the occupants arrived to reach the set point. However, at 4 pm the A/C turned on one hour before occupant departure.

#### ***Air Conditioning set points for early summer***

Table 1: Occupant's operation strategies to reduce use active cooling, occupants

Morning arrival (7 am - 11 am)	Close east window and louvers (Blocks the morning sun from heating up the space prematurely.) Open exterior sunspace doors (Allows the heat that builds up inside to escape before making its way into the living space.)
During a rain event	Close all doors, windows and clerestories (Prevent rain infiltration) Turn on the ERV (If exterior temp is lower than the interior temp) If AC is on, switch to unoccupied mode while away.
During mid-day hot period	Shut all doors, windows, and clerestories, close louvers Turn on AC (Occupied mode ON)
After mid-day heat (6:00 pm - 11:00pm)	Turn off AC (Open Doors/Windows mode ON) Open lower windows and clerestories (Flushes out heat)

Similar issues became apparent regarding set points during early summer, when climate conditions are usually mild and not yet too humid to require active cooling. For example, on

June 4<sup>th</sup>, the occupied schedule was set to start at 6:45 am CDT with an occupied cooling set point of 73°F / 22.78 °C and unoccupied cooling set point set of 82°F / 27.78 °C. With early morning temperature already at 76°F / 24.44 °C at 6:45 am the AC will turn on and keep the building at 73°F / 22.78 °C until the occupants arrive and turn on ‘Open Doors/Windows’ mode. With the intent to keep AC from operating until after ‘Open Doors/Windows’ is turned off, then the last person leaving should schedule the ‘Occupied Start Time’ for 30 minutes after the expected arrival of the first occupant. Another important observation was that the outdoor temperature usually doesn’t drop below the 73°F / 22.78 °C until 8 to 10 pm CDT and had high humidity content, thus night flush ventilation should be scheduled for around 3 am and morning arrival (assuming morning arrival is before the outside temp starts to rise). Night flushing should be sufficient to postpone AC usage until the middle of the day. Occupants tolerated slightly increased morning humidity for the sake of energy conservation, while afternoon humidity was considered uncomfortable.

### Detailed Data Visualization and Observation

To show case the above observations in detail, one typical day in winter is presented. Saturday February 27<sup>th</sup>, 2016 was still a net-energy-consuming day. The night before was cold at 30 °F / -1.11 °C and the heat turned on. The house was occupied from 8 am to 7pm. The day itself was mild and sunny with temperatures ranging from 30 °F / -1.11 °C at 5am to 59°F / 15 °C between 2pm and 3pm. The day had good electrical energy production, good solar water heating, and high energy consumption, which summed up to 7.1 kWh daily net CONSUMPTION and 1774 kWh cumulative net CONSUMPTION since Jun 16<sup>th</sup> as Figure 4 and 5 demonstrate.

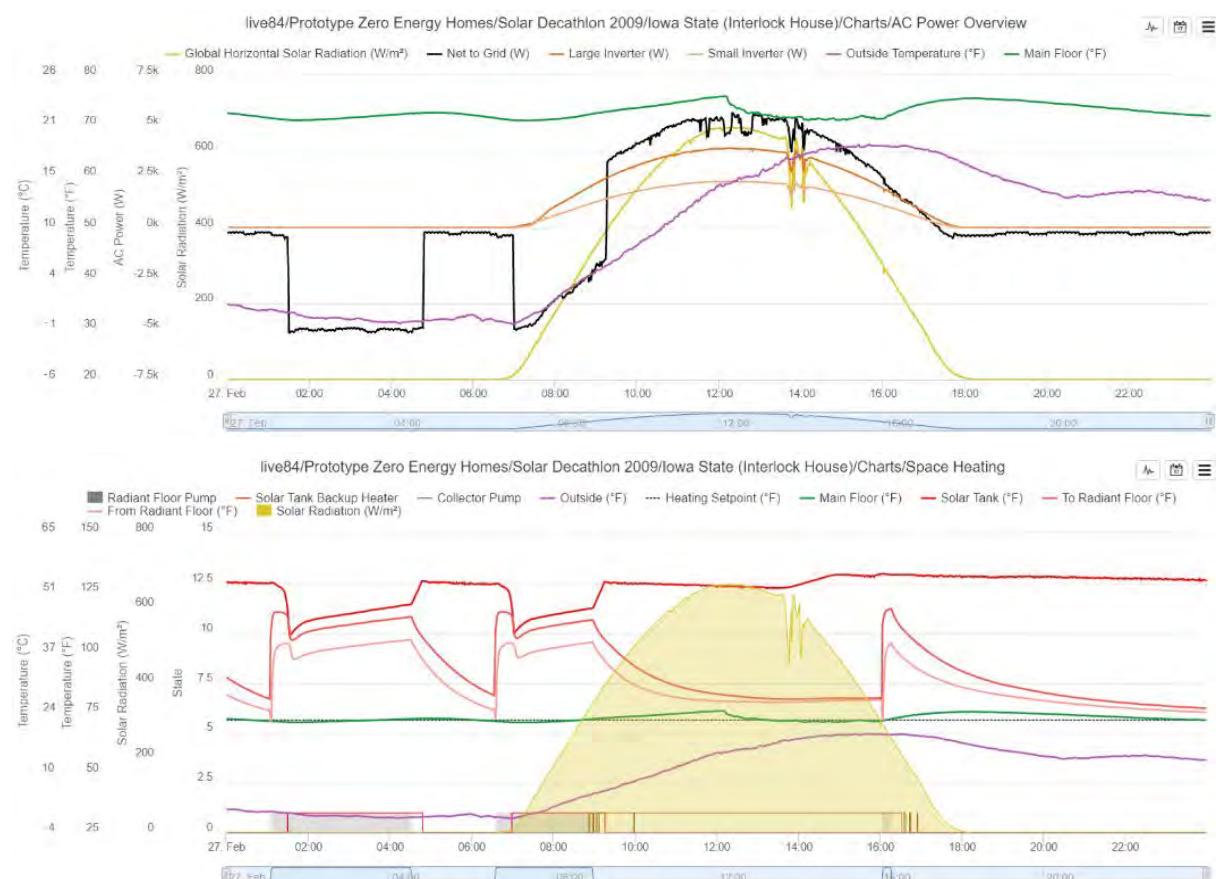


Figure 5: Typical winter day: a) Indoor Conditions and Solar Production; b) Space Heating and Solar Resources

## **Discussion of results**

The thorough analysis of the daily energy performance data revealed important time-dependent relationships between outside weather conditions, comfort desires, set point schedules and the ability to achieve the net-zero energy goal for the US Midwestern climate. While the current control system does not have the capability to create variable schedules for each day of the week, future net-zero energy homes using solar thermal energy in this climate should be equipped with predictive control strategies. For summer conditions, setting the “Occupied Schedule End Time” to 5pm or to 7 pm CDT can make an enormous difference for cooling energy needs. Wider range of set points and fine-tuned schedules as well as the use of an energy recovery ventilator (ERV) have proven to be critical. Occupant comfort is determined by multiple factors and occupants are leaving at 5 pm, switching to a wider set points before 5 p.m can save energy and bring the home closer to the net-zero energy goal.

## **Conclusion**

The discussed control strategies would require further long term testing before adapting them to a broader audience and other climate zones in order to determine the amount of energy consumed/saved by balanced occupant control. In conclusion we suggest, that buildings designed for a net-zero energy balance are carefully simulated based on a variety of schedules, set-points and operation scenarios to anticipate and discover potential challenges ahead. Thus as technology and design strategies as well as energy modelling tools have matured, the next research area to achieve an energy balance powered by renewable energy sources is occupant-building interaction, microclimate and refined operation and control strategies to thrive with less, yet without sacrificing comfort. Currently these buildings in the Midwest might still need austere occupants using predictive controls for optimal set-points.

## **References**

- He, S., Passe, U. (2014). “The potential energy efficiency of a hybrid designed house: A post-occupancy case study on the heating and cooling system”, ASHRAE 2014 Annual Conference, Track 8: Installation, Commissioning, Operation, Maintenance of Existing Buildings, Seattle, June 2014.
- Hong, Tianzhen. (2014). Occupant Behavior: Impact on Energy Use of Private Offices. ASim 2012 - 1st Asia conference of International Building Performance Simulation Association., Shanghai, China, 11/25/12-11/27/12. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory. LBNL Paper LBNL-6128E. Retrieved from: <https://escholarship.org/uc/item/6jp5w8kn>.
- Jeanblanc, E., He, S., Passe, U. (2016). Occupant-Centered Building Operation Strategies for Balancing Thermal Comfort and Energy Efficiency in Warm and Humid Climates. In Nicol, F., Roaf, S., Brotas, L., Humphreys, R., (Eds.), Making Comfort Relevant, Proceedings of 9<sup>th</sup> Windsor Conference, Cumberland Lodge, Windsor, United Kingdom. April 7-10 2016. Network for Comfort and Energy Use in Buildings, <http://nceub.org.uk>.
- Leysens, I., Passe, U. (2014), Towards an adaptive dynamic daylighting comfort understanding’. In: Nicol, F., Roaf, S., Brotas, L., Humphreys, R., (Eds.), Counting the Cost of Comfort in a Changing World, Proceedings of 8th Windsor Conference: Cumberland Lodge, Windsor, UK, 10th-13th April 2014. Network for Comfort and Energy Use in Buildings, <http://nceub.org.uk>.
- Passe, Ulrike, Evaluating passive and active solar design and performance interaction: First measured results (2012), in Proceedings of The Second International Conference on Building Energy and Environment (COBEE), August 1-4, 2012, Boulder, Colorado, edited by Dr. Zhiqiang Zhai, Dr. Xiangli Li and Haidong Wang, 2012: 265.
- Passe, U., Deza, M., Ganapathysubramanian, B., He, S., Vansice, K., Xu, S. (2016). Typological studies for passive design strategies based on coupled measured and modelled data. Proceedings of the 2016 Simulation for Architecture and Urban Design (SimAUD) conference, May 16-18, 2016, London.
- Passe, U., Timothy Lentz (2016) Designing Passive Solar Heated Spaces, in: Low energy low carbon architecture: recent advances and future directions, edited by Khaled Al Sallal, CRC Press, Taylor and Francis.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Exploring the influence of contemporary facade design on occupant satisfaction: a preliminary study in office buildings

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**Abstract:** This paper describes the preliminary findings of a post-occupancy evaluation campaign conducted on contemporary and energy-efficient office buildings with different façades treatments. The aim is to investigate occupants' comfort and perceived productivity and to observe to what extent the space appearance and the façade design play a role in the ultimate user's satisfaction and overall comfort. Two Swiss office buildings with different vertical enclosures are considered for this preliminary study: one has regular-shaped windows and regular blinds while the other presents a double-skin façade with a coloured silk-printed pattern partially covering the external pane and semi-transparent internal roller blinds. The results reported in this paper relate to an on-line extensive survey distributed among the buildings occupants to provide a global estimation of the comfort and perception they experience in their office. Findings suggest that in case of high dissatisfaction with some environmental factors, these influence strongly people's overall comfort evaluation but not the self-rated productivity. However, when comfort ratings are less critical – though not optimal-, overall comfort as well as perceived productivity are more strongly correlated to the pleasantness of the space than to the environmental factors. Nevertheless, in the case of patterned glazing, the façade design has a low influence on comfort perception. The study suggests that further research should be conducted, especially to look at façade designs that play a greater role in determining the appearance and/or a certain level of personal environmental control in a workspace.

**Keywords:** Façade design, Post-Occupancy Evaluation, Energy, Comfort, Perception

### Introduction

In the last 20 years, comfort research in field studies has called the attention to the necessity to study human satisfaction in real contexts (Boardass, 2003) and to broaden the comfort debate from physiological to also psychological and behavioral aspects (Cole, 2008).

According to Meir et al. (2009), post-occupancy evaluation (POE) can play a role in determining "an acceptable balance between creativity and utility" in the building procurement process, by assessing if and how the design elements interact with elements of user satisfaction (including comfort). In the contemporary architectural context, this question is particular relevant if we think about the rapid advancement of façade design technologies in providing architects and engineers additional potential for the achievement of both high energy and aesthetic performance.

To our knowledge, the way comfort studies have looked at user satisfaction and behaviour under different façade systems has been indeed rather limited, and restricted to the consideration of single "conventional" façade components (regular-shaped windows

and common shading systems), being the factors explored in relation to indoor comfort normally the window dimension, the preferred configuration for window shading (generally venetian blinds, louvers or roller blinds), and the occupant behaviour in operating both windows and blinds. Very little is known about the possible implications that the aesthetics of a façade can have on the overall acceptability of an indoor space. This holds particularly true for unconventional work space façade solutions such as silk-screen printed glazing or patterned shading devices.

This paper shows the preliminary results of a POE campaign that is currently being conducted on different office buildings located in Switzerland. The objective of this POE is to explore whether there exists a correlation between people overall comfort or self-rated productivity and their rating of the space appearance, workspace adjustability and design factors in those buildings where the façade plays a prominent role in determining the aesthetics of the workspace and the personal control of the environment.

## **Methodology**

### ***Case studies description***

The POE campaign was carried out in two Swiss office buildings. The criteria for the selection of the two case studies required them to be comparable in dimension, age of construction, occupation and function and to be designed according to energy-efficient principles. From an architectural point of view, although workspaces of the two buildings are comparable in terms of size, layout and furniture, they distinctly differ for the façade treatments: one (B1) has regular-shaped windows and typical horizontal metal venetian blinds (grey colour) while the other (B2) presents a double-skin façade with a coloured silk-printed pattern on the external pane and semi-transparent internal roller blinds (Figures 1 and 2). The buildings were conceived to have fixed, non-openable windows. Following employees' pressing requests for thermal conditions improvement, operable windows were installed in B1. Occupants were however advised against opening them.



Figure 1. Schematic representation of the façade types used in the case studies: B1 (on the left) and B2 (on the right)

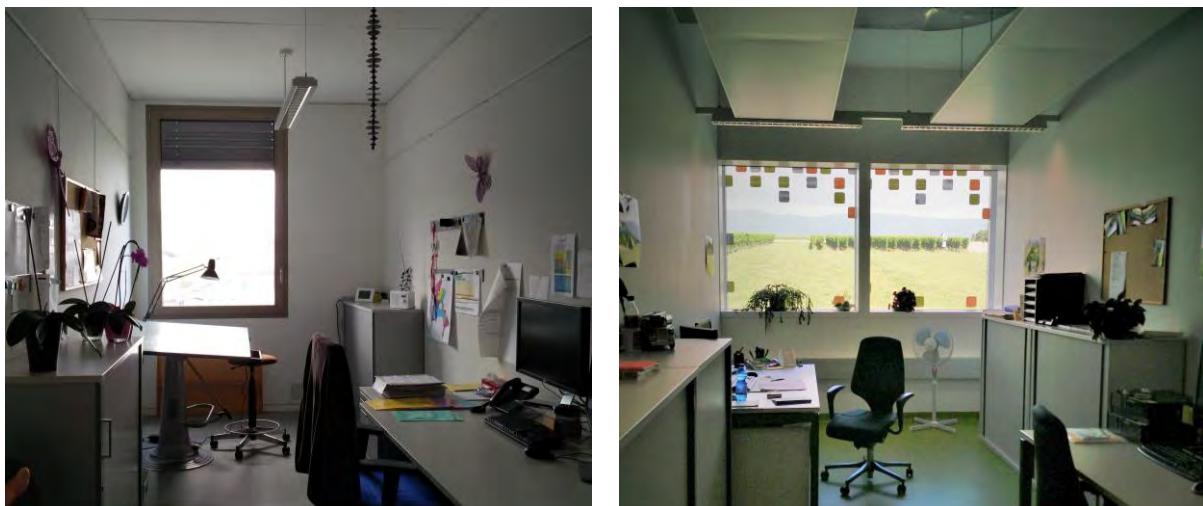


Figure 2. Examples of offices monitored during the POE in B1 (on the left) and in B2 (on the right) where the different façade treatments can also be noticed

Both buildings obtained the Minergie-P certification, a label attesting the high energy efficiency of new and refurbished buildings in Switzerland. This certification system relates primarily to the annual energy used by the building for heating, hot water and electrical ventilation, requiring air-tight building envelopes and the use of energy-efficient ventilation system. Particular attention is also paid to thermal comfort, especially to avoid the risk of overheating in summer. One of the two buildings obtained the additional "Eco" label, which resulted in further comfort criteria to be addressed with respect to light, air quality and protection against noise.

### **POE protocol**

The post-occupancy monitoring was conducted along two weeks at the end of winter 2017. The POE protocol consisted of:

- A two-week environmental monitoring campaign: temperature and relative humidity data loggers as well as illuminance-meters were installed in some work spaces.
- Point-in-time environmental monitoring episodes: two point-in-time measurement campaigns per building were also performed for instantaneous recording of temperature, relative humidity, illuminance, luminance distribution and air quality.
- An on-line extensive survey: a questionnaire was sent to the buildings' occupants to investigate the level of satisfaction they had experienced in the last 6 months (autumn-winter). The survey included 40 questions about the overall comfort and the indoor environmental quality (IEQ) factors (temperature, light, air quality and noise), the view to the outside, the perceived productivity and the personal environmental control (PEC) level. In addition, several non-environmental questions connected to design aspects and perception of the space were included in the survey. Responses were registered through a 7-point Likert scale. Additional open questions allowed the participants to add their own comments.
- Point-in-time surveys: along with the point-in-time measurements, occupants were also requested to give feedback about their instantaneous comfort within a short survey.

Table 1. Distribution of participants for the two buildings and the two surveys

<b>Occupant responses</b>	<b>B1</b>	<b>B2</b>	<b>Total</b>
Long-term survey	28	23	51
Female	11	14	25
Male	17	9	26
Point-in-time survey	40	32	72
<b>Total</b>	<b>68</b>	<b>55</b>	<b>123</b>

As shown in table 1, the groups of responses were comparable in terms of distribution of size and gender. The same protocol will be repeated during the spring-summer season in order to enable a full year evaluation.

In this paper only the responses of the long-term survey are analysed and commented.

### Results from long-term surveys

#### *Comfort factors*

Figure 3 shows the distribution of occupants' satisfaction with the IEQ factors and overall comfort. With regard to the perceived overall comfort, in both buildings the portion of dissatisfied people was less than 50%. However, while in B2 64% of the occupants reported a satisfying opinion, this percentage is only 32% in B1 (more neutral answers than in B2).

Lighting was the only IEQ factor with a positive vote assigned by more than 50% of the respondents (68% in B1 and 55% in B2). Conversely, temperature and air quality were found to be the most critical factors in both buildings: despite the introduction of operable windows, 75% of people in B1 were dissatisfied with both temperature and air quality against the 41% and 50%, respectively, of occupants in B2. The main causes of dissatisfaction for thermal comfort reported in B1 were: not adequate temperatures (too hot or too cold) and not adequate air movements (too high or too low, air drafts vents). The most cited reason of dissatisfaction in B2 were: absence of personal control and not adequate temperatures. In both buildings the occupants referred to dry, stiff and smelly air when describing the main causes of dissatisfaction with air quality. Among the people dissatisfied with the acoustics (39% of people in B1 and 45% in B2), a significant majority attributed as reasons of discomfort the noise coming from the building systems and the presence of other people in the building. In addition, sound reverberation issues were also reported in B1.

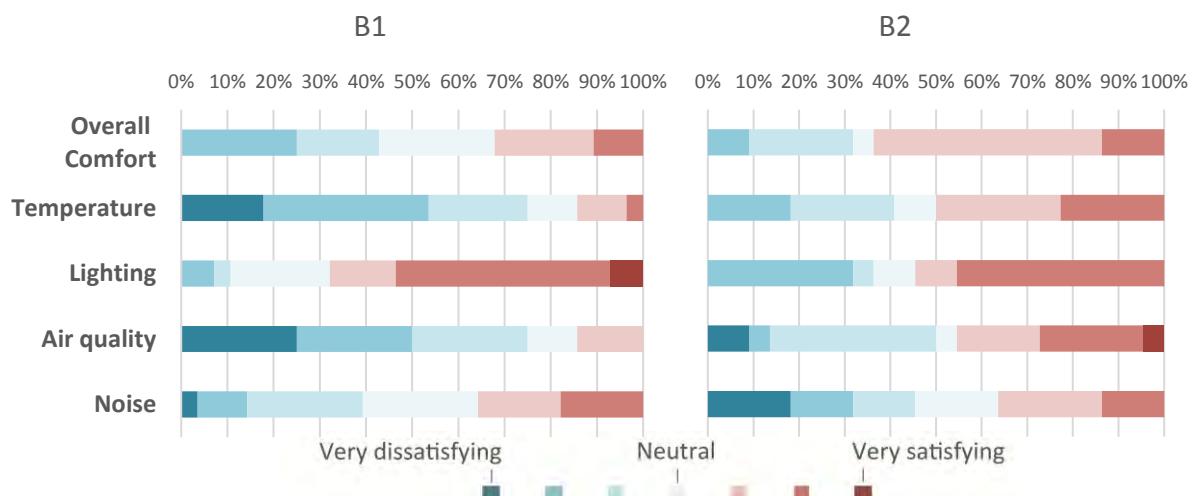


Figure 3. Occupants' ratings of IEQ factors and overall comfort in the two buildings

### **Design factors**

Participants were also asked to give their opinion about the appreciation of some design aspects such as the layout of the office (e.g. space, furniture, storage...), the decoration and the building façade (Figure 4).

It resulted that around 40-60% of occupants appreciate in a certain measure the layout and/or the decoration of the work spaces in both buildings. Conversely, the façade rating was very different between the two group samples: 64% of respondents reported a positive vote in the building with the patterned façade, as opposed to the 7% only of the building with the conventional façade.

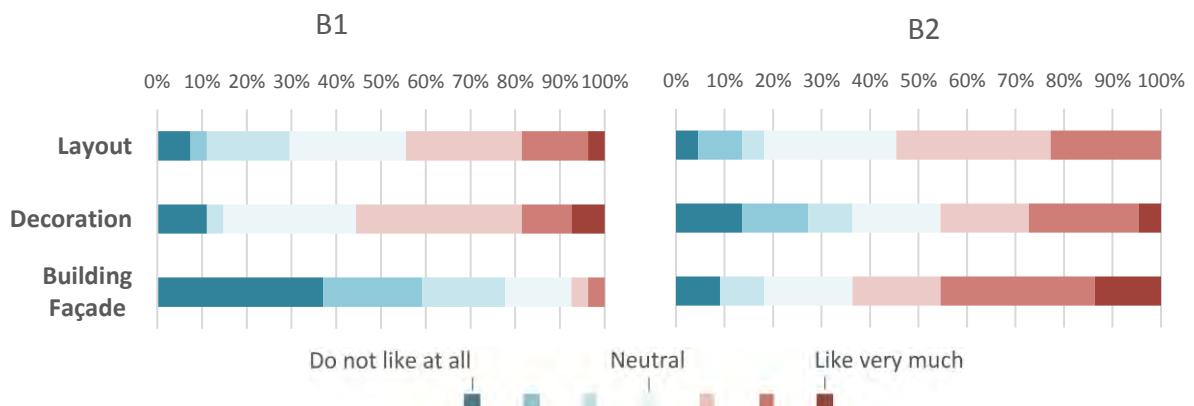


Figure 4. Occupants' ratings of design aspects in the two buildings

Participants were also asked about the general pleasantness of the space. To that question, respondents in B1 gave 57% of positive votes and 25% of neutral answers. In B2 11% more positive answers were counted (68% of satisfied) with 14% of neutral opinions.

### **Other factors**

Figure 5 shows the distribution of votes with regard to other non-environmental factors such as the privacy level, the quantity and quality of the view to the outside and the personal control of the environment. Around half of respondents of the two case studies were satisfied with the privacy in their office. This percentage decreased when they were asked about the view to the outside (32% for B1 and 41% for B2) and dropped to just 14% and 5% when it came to the level of PEC. In particular, over 90% of the people in both buildings reported no or limited control on noise, temperature and ventilation, which is consistent with the related comfort rating.

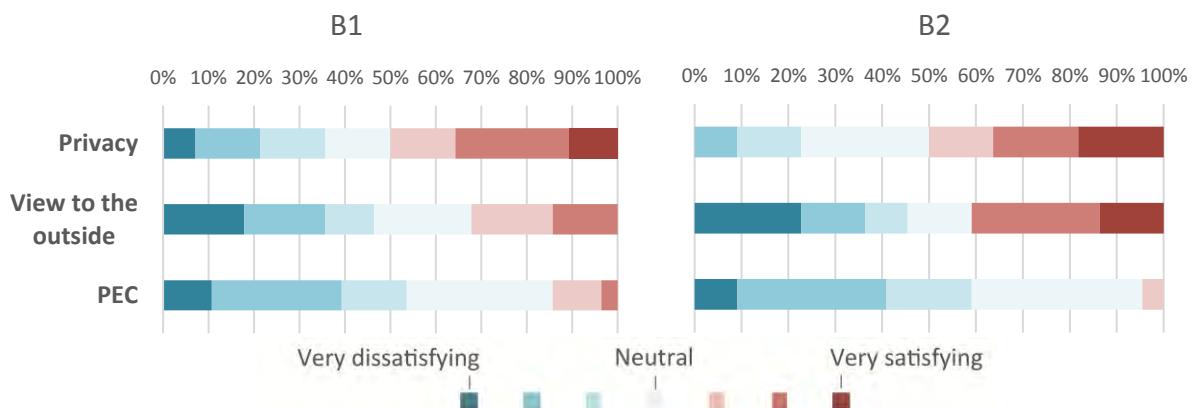


Figure 5. Occupants' rating of privacy, view to the outside and personal environmental control in the two buildings

### **Influence of variables on overall comfort and on self-rated productivity**

As the research produced Spearman correlation was run to determine a possible relationship between overall comfort or the self-rated productivity and the other rated environmental and non-environmental factors. Spearman's r coefficient ( $r_s$ ) is a measure for calculating the correlation between the two variables. The closer the  $r_s$  is to 1 the stronger the association, the more likely the effect of the given variable on the overall comfort or perceived productivity. In interpreting the outcomes, benchmarks were used to indicate low ( $0.30 \leq r_s < 0.49$ ), moderate ( $0.50 \leq r_s < 0.69$ ) and high ( $0.70 \leq r_s \leq 0.89$ ) correlation (Asuero et al., 2009). Values of  $r_s < 0.30$  were considered negligible, therefore excluding the variable to have any relevant effect.

P-value was also calculated to assess whether the results were statistically significant, i.e. if the null hypothesis (no correlation between the factors;  $r_s=0$ ), could be rejected. For this type of analysis a significance level  $\alpha = 0.05$  is generally used, meaning that the null hypothesis is rejected when  $p < 0.05$  and not rejected when  $p > 0.05$ .

As it can be observed in table 2, in B1 air quality is the only variable that is found to have a high correlation with overall comfort. Moderate correlations are found with decoration, PEC, layout, temperature and privacy, while low correlation emerged with the pleasantness of the space. These results reveal a strong influence on the overall comfort of the environmental factors perceived as the most critical and, conversely, of the design factors perceived as the most positive. The same factors don't seem to have any correlation with the self-rated productivity, except for a moderate influence of the pleasant space perception. Noise is also found to have a low influence on the productivity but not on the overall comfort.

In B2, where the comfort votes were more homogenous and less critical than in the other building, the pleasantness of the space appears as the most influential factor (high correlation) on the overall comfort but not on the perceived productivity. The office layout, PEC and noise have a moderate effect.

Despite the effect provided by the pleasantness of the space, the façade design seems to have no effect in the building with a conventional window design and a low effect in the offices with the partially patterned windows.

Table 2. Variables influence on overall comfort and self-rated productivity ratings for the two buildings.

Spearman's  $r_s$  and p-value are shown (significance level  $\alpha = 0.05$ )

	Overall comfort				Self-rated productivity			
	B1		B2		B1		B2	
	$r_s$	p-value	$r_s$	p-value	$r_s$	p-value	$r_s$	p-value
Temperature	0.53**	0.004	0.38	0.082	0.22	0.246	0.32	0.151
Air quality	<b>0.72***</b>	<b>0.000</b>	0.03	0.869	0.07	0.731	-0.02	0.916
Light	0.25	0.205	0.46*	0.034	0.23	0.246	0.21	0.356
Noise	0.33	0.083	0.67**	0.001	0.38*	0.048	0.26	0.236
Pleasantness space	0.43*	0.022	<b>0.74***</b>	<b>0.000</b>	0.55**	0.003	0.34	0.119
Façade	0.020	0.918	0.41*	0.057	0.07	0.727	0.13	0.565
Layout	0.54**	0.003	0.52**	0.014	0.28	0.148	0.20	0.361
Decoration	0.57**	0.001	0.41*	0.058	0.30	0.122	0.33	0.133
View to the outside	0.13	0.497	0.356	0.105	0.00	0.980	0.34	0.124
PEC	0.54**	0.004	0.58**	0.006	0.28	0.115	0.28	0.207
Privacy	0.50**	0.007	0.087	0.699	0.01	0.939	0.32	0.151
Self-rated productivity	0.30*	0.041	0.53**	0.013				

\* low correlation, \*\* moderate correlation, \*\*\*high correlation

A linear regression analysis (Figure 6) indicates the relationship between the pleasantness of the space on the overall comfort in the two buildings, although the boundary conditions for the application of this statistical model have not been verified yet.

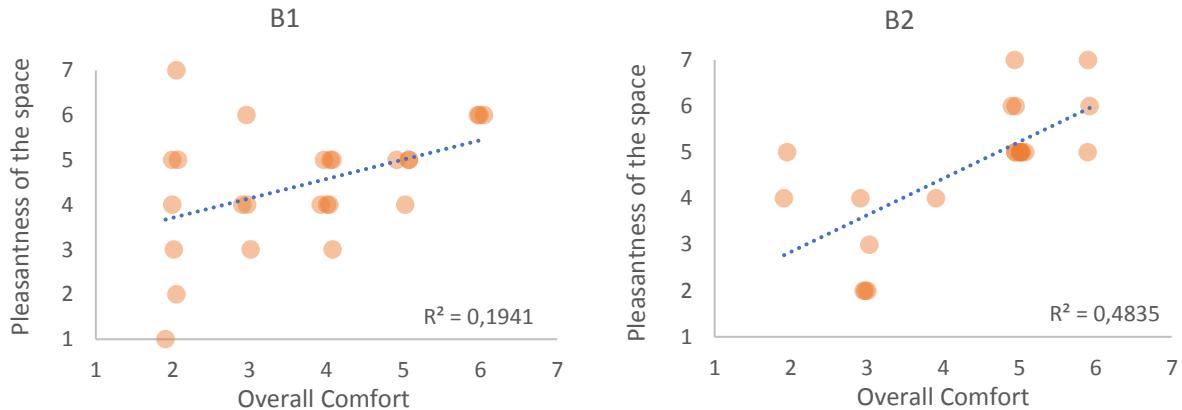


Figure 6. Linear regression model showing the relationship between overall comfort and pleasantness of the space

## Conclusions

The study described in this paper is part of a broader POE campaign aimed at exploring building users' satisfaction in contemporary Swiss offices, with a particular focus on buildings where the façade can play a major role in determining the appearance and/or a certain level of personal environmental control. One of the premises for the buildings comparison is that they should respect some common high-energy design standards.

In this paper, the preliminary outcomes of an extensive comfort and perception survey distributed to people working in offices with a conventional façade system are analysed and compared with those of people working in a building with an unconventional façade system.

The first evidence that resulted from this study is that, despite the high energy design requirements, both the buildings seem to perform poorly in meeting users' expectation with comfort. Except for lighting, all the investigated IEQ factors obtained a satisfying score from less or equal 50% of respondents, with thermal comfort and air quality appearing as the main criticalities. This is particularly evident in B1, despite the adjustments provided to the windows to enable an increased personal control on temperature and ventilation.

Limitations in façade-dependant workspace adjustments, i.e. solar and natural ventilation control, are perceived by the majority of respondents as a factor of dissatisfaction, which is consistent with several comfort studies on green buildings (Wagner et al. 2007, Healey 2013) as a consequence of air-tight and mechanically ventilated sustainable design concept. This results also in a moderate correlation, in both cases, of PEC with the overall comfort but not to the self-rated productivity.

In line with previous studies about comfort, it was found that when users are particularly dissatisfied with some IEQ factors, these last play the main role in people's overall comfort.

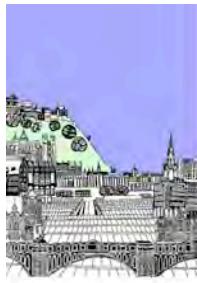
However, the research showed that when comfort ratings are less critical, users appear to be happier with the overall comfort mainly when the space where their work

looks pleasant. Among the explored design factors, the layout of the space resulted as the one with the major influence, in line with existing studies (Schiavon & Altomonte, 2014; Leaman & Bordass, 2001; Baird et al.. 2012; Frontczak et al., 2012; Kamaruzzaman et al. 2015). In the case of the patterned glazing, the façade design seems to barely affect people comfort perception, thus not providing any significant evidence about the influence of façade design on building occupants satisfaction.

Nevertheless, these first findings suggest the need for further research in this direction and confirm the necessity to account for a “re-contextualized notion of comfort” (Cole et al. 2008), as a state of mind where both environmental and non-environmental factors -including aesthetics- can have a key role for people’s satisfaction at work. In particular, these results encourage to explore situations where more “extremes” façade design configurations can be adopted. This would serve to assess to what extent an increased aesthetic presence can affect the users’ satisfaction with the workplace and to gain, as a consequence, a deeper and more comprehensive understanding to move towards optimal design.

## References

- Asuero G., Sayago A., González A. G. (2006). The Correlation Coefficient: An Overview. *Critical Reviews in Analytical Chemistry*. 36(1). pp. 41-59
- Baird G., Leaman A., Thompson J. (2012). A comparison of the performance of sustainable buildings with conventional buildings from the point of view of the users. *Architectural Science Review*. 55(2). pp.135-144.
- Boardass B. (2003). Learning more from our building-or just forgetting less. *Building Research and Information*. 31(5). pp. 406-411
- Boardass B., Leaman A., Ruyssevelt P. (2001). Assessing building performance in use 5: conclusions and implications. *Building Research & Information*. 29(2), pp. 144-157.
- Frontczak M., Schiavon S., Goins J., Arens E., Zhang H., Wargocki P. (2012). Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air*. 22. pp. 119–131.
- Healey, K. H. (2013). Unforgivable: exploring thermal comfort, adaptation, and forgiveness in a problem green office building. In: Marc Aurel Schnabel, *Cutting Edge: 47th International Conference of the Architectural Science Association (ANZAScA)*, Hong Kong, China. 13-16 November 2013.
- Kamaruzzaman S.N., Egbu C.O., Zawawi E.M.A., Karim S.B.A., Woon C.J. (2015). Occupants' satisfaction toward building environmental quality: structural equation modeling approach. *Environmental Monitoring and Assessment*. 187(242). pp. 1–21.
- Leaman A., Bordass B. (2001). Assessing building performance in use 4: the Probe occupant surveys and their implications. *Building Research & Information*. 29 (2). pp. 129-143.
- Meir I. A., Garb Y., Jiao D., Cicelsky A. (2009). Post-Occupancy Evaluation: An Inevitable Step Toward Sustainability. *Advances in Building Energy Research*. 3(1). pp. 189-219.
- Raja, I. A., Nicol, F., McCartney, K. J., Humphreys, M. A. (2001), Thermal Comfort: use of controls in naturally ventilated buildings, *Energy and Buildings*, 33, 235-244.
- Schiavon S., Altomonte S. (2014). Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings. *Building and Environment*. 77. pp. 148–159.
- Stevens, S. (2001), Intelligent facades: occupant control and satisfaction. *International Journal of Solar Energy*. 21 (2-3). pp. 147-160.
- Wagner A., Gossauer E., Moosmann C., Gropp T., Leonhart R. (2007). Thermal comfort and workplace occupant satisfaction – results of field studies in German low energy office buildings. *Energy and Buildings*. 39. pp. 758-769.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Impact Of Constructivism Density Of The Urban Tissue In Improving The Urban Ambience- Thermal, Visual - Of The Street. For Saharian Cities Case Study Of The City Of Biskra

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**Abstract:** The role of urban tissue is important for protecting the free space –street- of the physical environmental loads, where the attenuation of convection, light and the sound of the natural environment surrounding. This research is trying to identify the role of the constructivism density of the tissue, through the comparison of two main axes of the physical ambience, they are -the thermal ambience, and the visual ambience. Where has been adopted the methodology of the research is comparative method, which is based on a comparative method of the ambience physical elements. Where we was also adopted the research performance by raise the real values of the physical ambiences every two hours, each three consecutive days, through the measurement stations that are positioned via the three types of the street engineering ( $H \geq 2W$ ,  $H=W$ ,  $H \leq 0.5W$ ). And through the results obtained we conclude that we can note the values difference between the three types of street engineering. Where was the street of the high ratio between  $h/w$  ( $H \geq 2L$ ), which knows canyon street, is the less Physical loads. Thus turns out the impact of constructivism density protection the free space –street-. Where the relationship between constructivism density and section of street for the improving in the physical urban ambience.

**Keywords:** street, constructivism density , physical urban ambience , sensory perception ,urban tissue.

### Introduction

The attenuation of environmental loads, is the obligatory principle for the survival of the cities of the desert (Boukhbla et al, 2013), the question of the physical comfort of these cities, is re-value and the fundamental authenticity of these cities (Jean et al,2001). Where the role of urban tissue for protection of the free space –street- of the physical environmental loads.

### The problematic

The city of biskra is suffering from the problem of the increasing the environmental physical burden (Cote,2005). Where the increase of air temperature, increase natural lighting, strong winds, and noise, which cause many problems to the health of the human. This problematic raises the question of how to enable the reduction and improving of the physical urban ambience of tissue -street-.

## **The objectives**

- Studying the relationship of the effect of the H / W. To improve urban physical comfort in urban space - street-.
- Identifying the best of the typical relationship between H / W, to improve urban physical comfort in space -street- through comparative study between them.

## **Methodology**

The comparative method is the scientific methodology for this research. Where the theoretical axis, and the practical axis, this is the last where three axes. The first, identifies the urban environment. The second. Determines the tool to search, the field work. The third, is a process of analysis, interpretable, by the comparative method and the discussion of the results .

## **The theoretical part**

### ***The physical Ambience***

We can understand the concept is of the physical ambience by the concept of the physical comfort, this is the last where five head consists. It is thermal comfort, visual, acoustic and olfactory.

#### ***Thermal comfort***

The concept of thermal comfort Formed by combinations the climatic factors that affect the heat exchange between climate and human (Allen, 2011) , So the thermal comfort is zone a very short period within a period of thermal equilibrium. That area reflects interaction the components and combinations the climatic factors that affect the heat exchange between climate and human, to reach the case of thermal equilibrium. Those elements which comprise the human activity that is practiced , the coefficient of thermal insulation of clothing, air temperature, air speed, relative humidity, and the average temperature of surfaces surrounding (Nikolopoulou, 2004).

#### ***Visual comfort***

The field of optical radiation for visual comfortable and visual perception in a range between 100 to 1000 lux. Where this area ensures levels of optical radiation for ease of performing the tasks and visual functions within the urban tissue (Loiseau et al, 1993), this area in which of shaded and sunny area, which is the cause of the human visual perception comfortable (Nikolopoulou, 2004).

#### ***Density Construction***

The responsible of the height of the facade is density Construction (Allain,2006). This density which is controlled by two criteria. The first is the coefficient of the exploitation of land (CEI). The second is the coefficient of the occupation of land (COI), (Panerai et al,2009).

Table 1. The different models of density Construction.

Altitude occupation of land	High or more (R + 6)	Medium (R + 2) to the (R + 5)	Low floor, ( R ) or (R1) R upper floor
A strong 50-100%	Skyscrapers centrality	Residential building in urban residential building mass without elevator	Houses a central space
Medium 50-20%	High barriers	Little group buildings, accommodation a median (individual entrances)	Collectively houses or stripe cities housing
A weak up to 20%	Towers in green spaces	Low land	Individual paired, individual single, pavilion

### **The different Models of The street Engineering**

The relationship between the architecture facade and the view of the street in three geometric patterns ( $H \geq 2W$ ,  $H=W$ ,  $H \leq 0.5W$ ).-( Open Street, dihedral street, Canyon street) ( Khaled,2008).

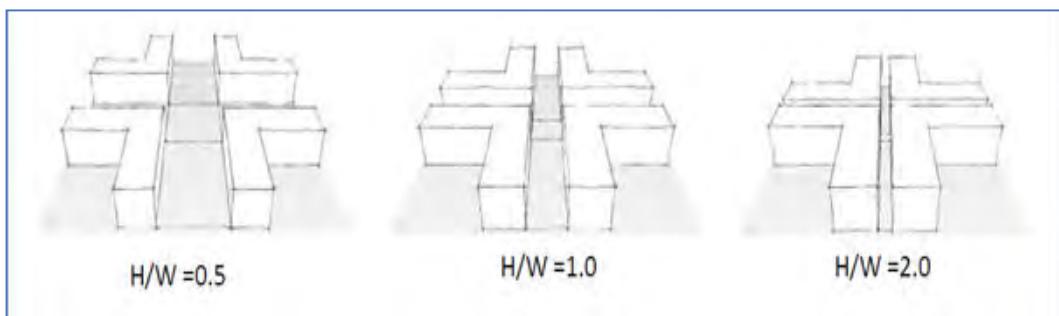


Figure 1. The different models of the street engineering. Source. Author.

### **The practical part**

#### **The site Measuring stations**

Distributing three stations on the tissues of the overall sample of the city as they are presented in the following figure. The street is according to the direction:(North-west/south-east).

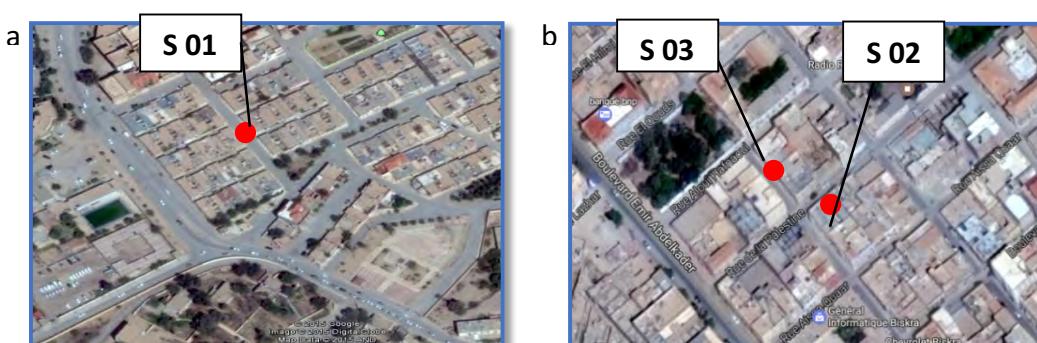


Figure 2. (a) The station (01). (b) the stations (03,02). source. google earth 2015.

### Description of measurement stations

*Station No. 01 . The low ratio between the height / width ( $H \leq L$ ). Open Street*

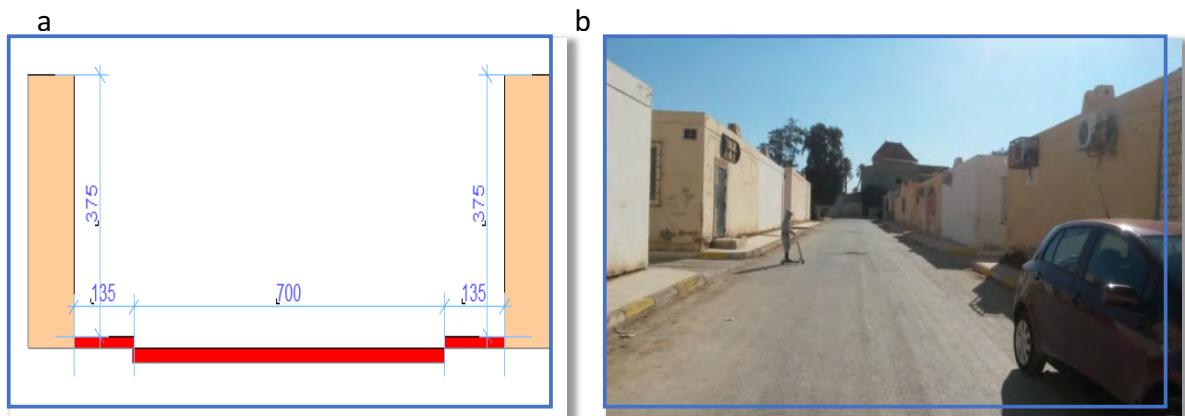


Figure 3. (a) Section of the station. (01) . (b) view of the station. (01). Source. Author.

*Station No. 02 . The average ratio between the height / width ( $H = L$ ). dihedral street*



Figure 4. (a) Section of the station. (02) . (b) view of the station. (02). Source. Author.

*Station No. 03. The high ratio between the height / width ( $H \geq 2L$ ). canyon street*

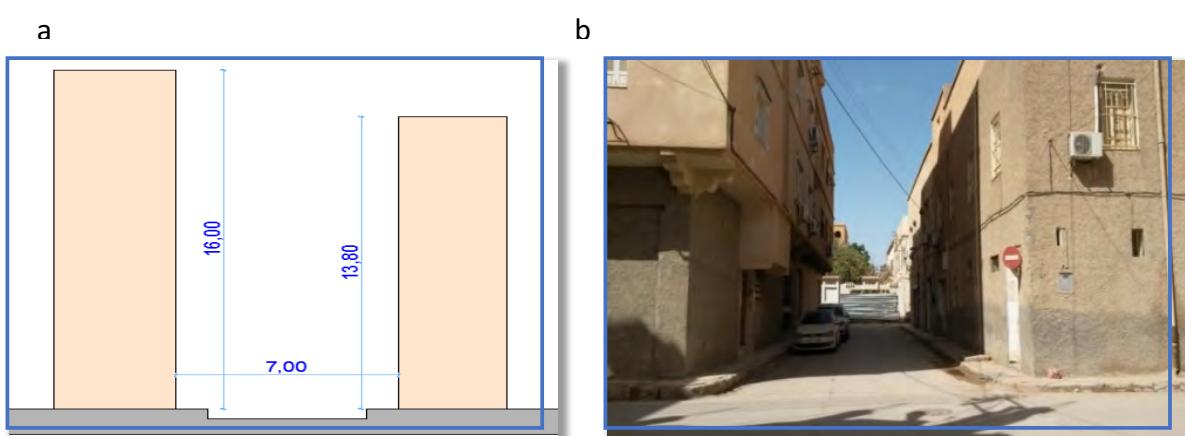


Figure 5. (a) Section of the station.(03) . (b) view of the station. (03). Source. Author.

## Measuring instruments used

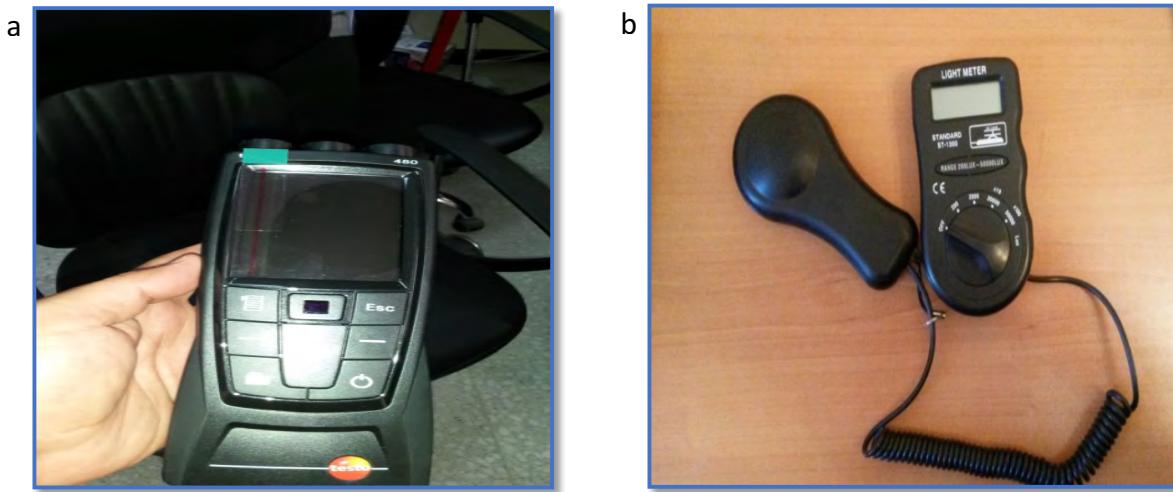
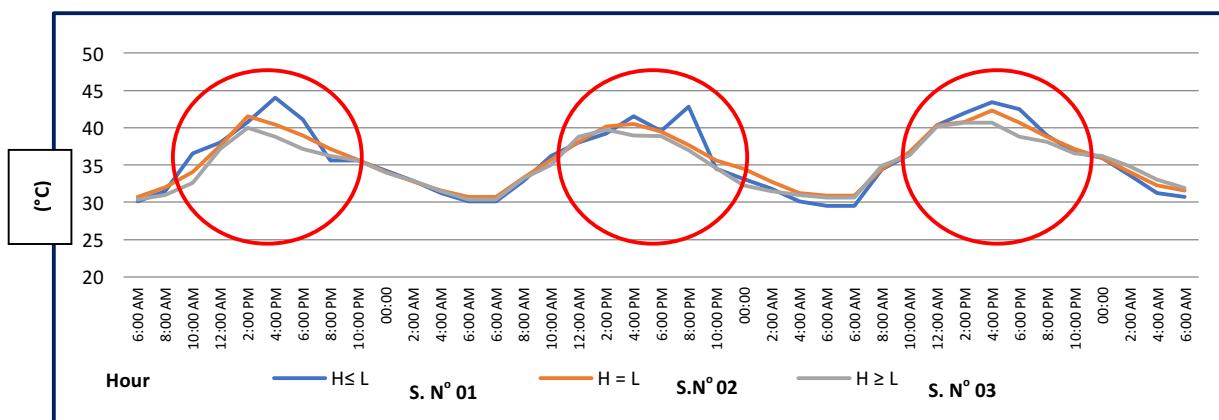


Figure 6. (a) Testo 480. (b) lux meter. (03). source. Author.

## Results and discussion

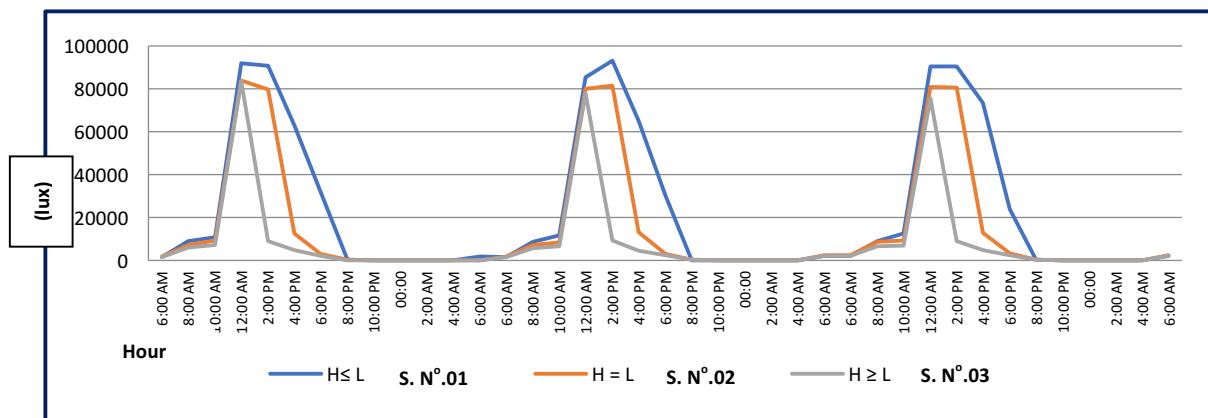
### Air temperature for the three models of Streets, north west / south east



graph 1. The level of air temperature. streets- North west / South east .Source. Author.

Through experience we record the station n°01: has higher values where they reached max a temperature of 44.4°, estimated total thermal energy 6326 W/m<sup>2</sup>/d. Then the station n°02: where the values max a temperature of 42.3°, and estimated total thermal energy 5314 W/m<sup>2</sup>/d. The station n°03 : where the values max a temperature of 40.6°, and estimated total thermal energy 3288W/m<sup>2</sup>/d. So we understand the temperature difference between the open street, canyon street, reached a 4°, and difference of estimated total thermal energy 3038 W / m<sup>2</sup>. This difference in values is consequent of difference in the ratio between h / w, where the lowest values was in the canyon street. This result prove the impact of constructivism density for protection the free space –street-, where the relationship between constructivism density and section of street in improving air temperature.

## ***The level of natural lighting for modes of streets, north west / south east***



graph 2. The level of natural lighting of streets. North West / South east. source. Author.

Through experience we record the difference of the values of natural lighting. Where the station n°01: higher values reached max of level of natural lighting  $90_{k/lux}$ , and estimated total lighting energy in direct lighting  $277.7_{k/lux}$ , this type of street is exposed to direct sunning, 08 hours of the day. Then the station n°02: the values max of level of natural lighting is  $90_{k/lux}$ , and estimated total lighting energy in direct lighting  $176_{k/lux}$ , this type of street is exposed to direct sunning 06 hours of the day. The station n°03 : the values max of level of natural lighting  $83.5_{k/lux}$ , and estimated total lighting energy in direct lighting  $83.5_{k/lux}$ , where the street is exposed to direct sunning only two hours of the day. So the difference of estimated total lighting energy is  $194.2_{k/lux}$  between the open Street, canyon street,. This difference is consequent of difference in constructivism density, where the canyon street - was Less time periods of direct sunning, and was less lighting energy. This result prove the impact of constructivism density, in improving of the level of natural lighting in the street. Where the relationship between constructivism density and section of street.

## Conclusion

We can say that the impact of the constructivism density of the urban tissue in improving the Physical urban ambience being in the relationship between constructivism density and section of street, where proportionality H/W of the street, controller of the effectiveness of reduce the physical loads for the environment applicable on the street and achieve the shade and alternation throughout the day. Thus turns out the impact of constructivism density of the urban tissue in improving the physical urban ambience, for desert cities.

## References

- Allain, R. (2006). *Morphologie Urbaine –Geographi Amenagement Et Architecture*: Paris. Armand Colin

Allen, K . Translation. Ahmed, K. (2011). *The Standards Of The Design Warm Areas*: Mketbh Anglo-Egyptian

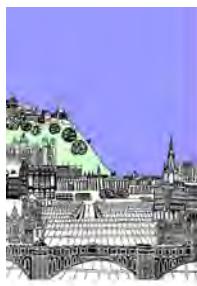
Boukhabla, M. Djamel, A. (2013). *The Effect Of Urban Morphology On Urban Heat Island In The City Of Biskra In Algeria*: International Journal Of Ambient Energy, Vol 34:2.P 100–110

Cote, M. (2005). *La Ville Et Le Désert*: Paris. Karthala

Jean, D. Edmond, B. (2001). *Les Milieux Désertiques*. Paris. Armand Colin

Khaled, O.(2008). *Contribute To The Project In The Island Of Thermal Analysis Indicators*: Memo Master. University Of Nantes

- Loiseau, M, J. Terrasson, E. Trochel, Y. (1993). *Le Paysage Urbain*: Paris. Editions Sang De La Terre
- Nikolopoulou, M. (2004). *Concevoir Des Espaces Extérieurs en Environnement Urbain: Une Approche Bioclimatique*. Centre For Renewable Energy Sources (C.R.E.S.) (<http://alpha.cres.gr/ruros/>) visit in 15/12/2015
- Panerai, P. Jean, C. Jean-C, D. (2009). *Formes Urbaines De L'ilot A La Barre*: Marseille. Editions Parenthèses



# PLEA 2017 EDINBURGH

*Design to Thrive*

## What do the traditional *pol* houses teach us for contemporary dwellings in India?

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**Abstract:** Indian real estate is trying to find appropriate solutions to provide thermally comfortable dwellings using passive design strategies. Historically, a big part of architectural teaching has been focused on learning about climate responsive strategies from vernacular buildings. However, such knowledge sharing was based more on observational studies as opposed to long-term scientific field studies with quantitative outcomes. The authors believe rigorous scientific enquiry is required to understand the performance of vernacular dwellings in order to encourage the use of climate responsive strategies. This study looks at the vernacular dwellings, called *pol* houses, as well as the contemporary dwellings to assess their thermal comfort performance. Indoor environmental conditions in these houses were monitored hourly for a year. Outdoor conditions were also recorded using a weather station simultaneously. Selected dwellings were compared on the basis of area, occupancy and socio-economic background. Thermal performance of these houses was evaluated against two models – the India Model for Adaptive Comfort (IMAC) and the ASHRAE Standard-55 adaptive model.

**Keywords:** Vernacular dwellings, Contemporary dwellings, Climate responsive design, India Model for Adaptive Thermal Comfort, Ahmedabad

### Background

India is currently experiencing high demand for new dwellings in urban centres. Increased pressure on land has led to the construction of multi-family, multi-storey housing units. Due to the ever increasing land prices, density of floor space and the lack of residential energy codes, the design of new dwellings is governed by the economics of floor space while climate responsiveness becomes a low priority. Poor building design necessitates the use of energy intensive technologies to achieve thermal comfort, making these new buildings very energy intensive. Increase in purchasing power and better affordability of home appliances also contribute to the increase in residential energy consumption. India is home to 1.3 billion people, about 18% of world's population with 6% of world's primary energy consumption. The population has doubled since 2000 and is on high growth trajectory (IEA, 2015). India accounts for about 220 million dwelling units with an average household size of 5.6 occupants per house (Shukla, Shnapp and Rawal, 2015). According to the 12th Five Year Plan (2012-17), India has deficit of 18.8 million dwelling units in urban India (Kundu *et al.*, 2016). In absence of deployment of energy efficiency measures in residential sector, electricity consumption may rise to approximately 1300TWh compared to approx. 250TWh now. With aggressive energy efficiency deployment, consumption may be curtailed at about. 550TWh (Shukla, Shnapp and Rawal, 2015). India being a tropical country, the cooling demand accounts for a large part of energy consumption, i.e. Kolkata has 3360 cooling degree days (CDD), New Delhi

has 3015 CDD, Mumbai 3469 CDD and Chennai 4108 CDD (Selvanathan and Migdalska, 2015). In view of India's future electricity demand for residential sector, it is important to utilize the climate responsive strategies in order to reduce energy consumption. Understanding the thermal performance of dwellings in response to the local climate is the key to evaluate their appropriateness. This paper explores possibility of learning from vernacular dwellings to quantify their thermal performances on the basis of field measurements.

### Literature review

A study conducted in Cyprus concluded that vernacular buildings used building layout and construction materials in varied climates as the means to achieve desired thermal performance (Philokyprou *et al.*, 2017). Rashid *et al.* (Rashid and Ahmed, 2013) conducted field measurements in Dhaka to conclude that Bangladesh traditional houses provide better comfort conditions throughout the year compared to contemporary houses. This study was based on simultaneous air temperature measurements in summer (June) in two houses located about 25m apart from each other. A study based on numeric calculations for heat transfer and field measurements for thermal sensation and indoor environment was conducted in North Sulawesi in Indonesia to compare ten traditional houses and ten modern houses. It concluded that traditional houses tend to cool down relatively quickly during afternoon, following the decrease in outdoor temperature, versus modern houses tend to retain higher indoor air temperatures until late evening (Sangkertadi, Syafriny and Tungka, 2008). A study conducted in composite climate of Nepal concluded that thermal performance of traditional houses was better than that of contemporary houses; new equations were developed to predict indoor thermal environment using outdoor temperatures for traditional and modern houses (Bajracharya, 2014).

A comparative study of three types of houses - traditional, designed solar passive and modern houses in India concluded that during summer period indoor temperatures of designed solar passive houses were similar to traditional houses and 2-3°C cooler than modern houses (Subramanian, Ramachandran and Kumar, 2016, 2017). A study conducted in hot-dry climate of Jaisalmer suggests that with high thermal mass, building indoor daily temperature range remains stable across the year (Matthews, 2000). A study in coastal region of India measured indoor summer temperatures in traditional houses in the range of 24-30°C with 60-75% relative humidity (RH) and 28-26°C with 50-77% RH range. It cited effective ventilation as the key contributor to thermal performance of traditional houses (Priya, Sundaraja and Radhakrishnan, 2012). Available literature suggests that traditional houses tend to provide better thermal comfort compared to contemporary houses. Use of better ventilation strategies and balance between thermal mass and insulation were identified as important lessons.

### Context

This paper presents a comparison of thermal performance of *pol* houses (PH) with contemporary houses (CH) in the city of Ahmedabad. It is a 615 year old city with a population of 5.8 million people spread across 450 km<sup>2</sup>. Approximately 0.35 million people live in traditional houses in the old part of the city, which is spread across 16 km<sup>2</sup> (Census of India 2011, 2011; Mahadevia, Desai and Vyas, 2014). Ahmedabad falls under the hot-dry climate zone according to the National Building Code of India (Bureau of Indian Standards, 2005). Using the ASHRAE Standard-55 adaptive thermal comfort model (ASHRAE, 2013) as reference, a typical building in Ahmedabad can be operated in natural ventilation mode for 20% of the

time annually (Figure 1). It will need dehumidification for 37%, mild cooling for 20%, cooling for 11% and cooling with dehumidification for about 9% of time annually (Shukla, Bansal and Rawal, 2012). The average outdoor temperature is more than 30°C during summer (April-June) and the maximum recorded temperature in May 2016 was as high as 48°C. Summer mean relative humidity (RH) remains around 53%. Monsoon lasts from July to October while the months of December to February bring a mild winter. November and March are transition months with average temperature of 26°C and RH of 50%.

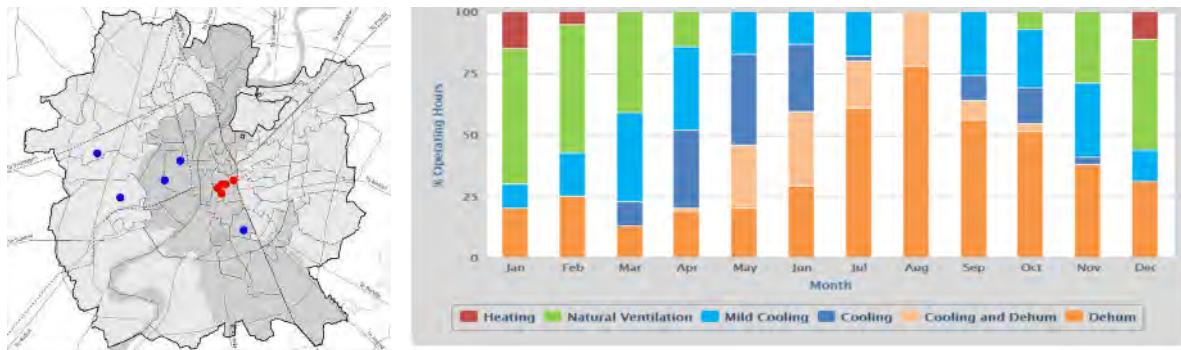


Figure 1 City map of Ahmedabad showing location of PH (red) and CH (blue); estimated operation modes for a typical building in Ahmedabad

## Methodology

This study is based on field measurement conducted between May 2015 and June 2016. Five PH and ten CH were measured for air temperature (°C), Relative Humidity – RH (%), and lux levels. This paper is based on five PH and five CH. Out of ten CH, five were selected for this study as their floor area was comparable to the PH typology. The average floor area of these 10 houses was about 112 m<sup>2</sup>. Three to five spaces in each house were monitored and hourly data was logged using the ONSET HOBO U-12 data logger. Surface temperature spot measurements was taken occasionally for internal wall surface temperatures using non-contact handheld laser based Fluke 561. Outdoor weather station was installed at a central location in the city to measure concurrent outdoor air temperature (°C), solar radiation (W/m<sup>2</sup>), RH (%), wind direction, wind speed and precipitation. It is important to note here that the outdoor conditions in city centre may differ slightly from the suburbs. Using a single source of outdoor weather data (from the weather station) may be considered one of the limitations of this study. Another limitation is that the monitoring data being analysed in this study includes typical/moderate summer conditions but not extreme summer conditions.

Figure 3 depicts measured indoor air temperatures in all spaces of all houses. First row depicts outdoor air temperatures during observation period, i.e. August 2015 to May 2016. Air temperatures from all spaces of each house are placed next to each other, but blank row is used to separate one house from another. Upper part of Heat map shows observations from PH and lower from CH. Monitoring data showed the houses were being operated in naturally ventilated mode for most part of the year. The floor-to-window ratio in these houses ranged from 1:16 to 1:37. Ventilation in CH occurred through the window/s on the facade and internal doors. Ventilation in PH occurred through window/s on the façade, internal doors, ventilators located above the doors and windows facing the courtyards. Due to high air changes per hour (ACH), surface temperatures and air temperatures were assumed equal.

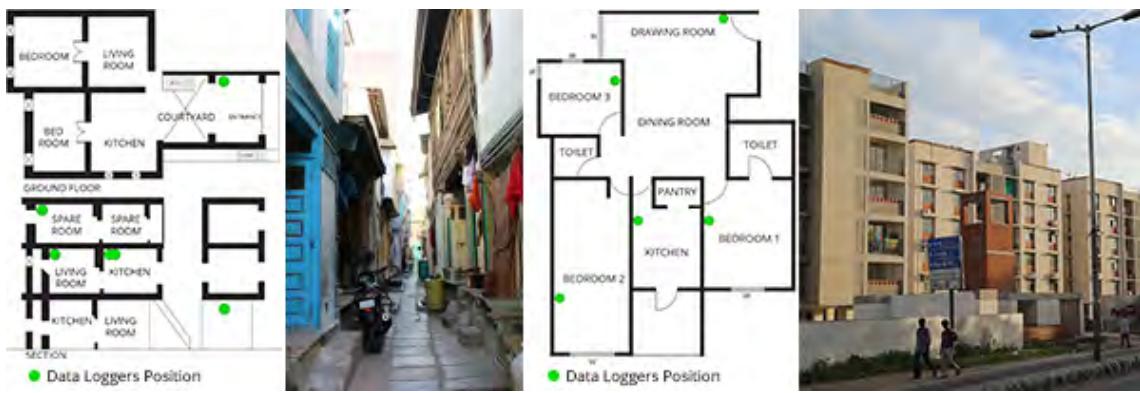


Figure 2 Plans of PH and CH with data logger positions (green dots) and photographs

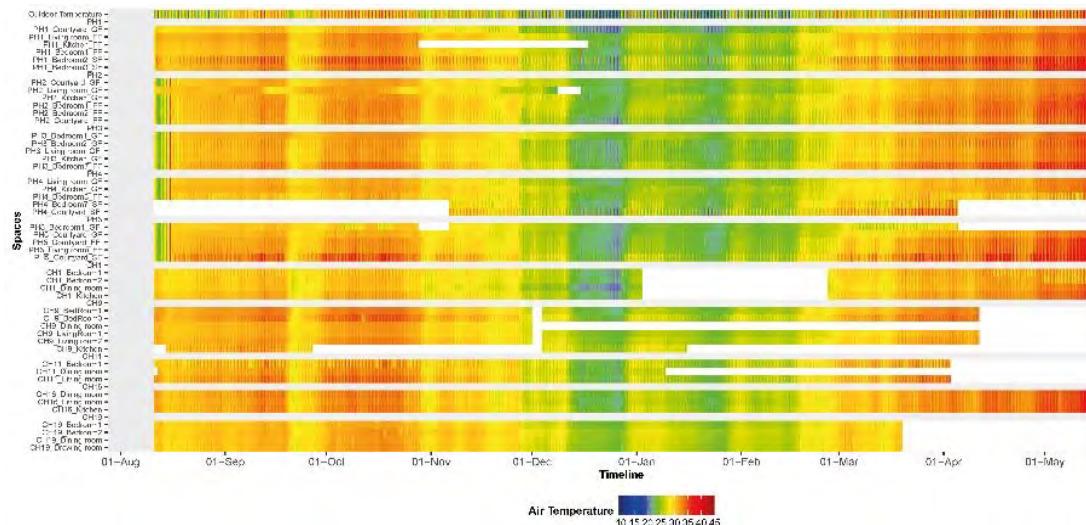


Figure 3 Measured indoor air temperatures in all spaces of all PH and CH

Measured indoor air temperatures were assessed against the 90% acceptability range as prescribed by the India Model for Adaptive Thermal Comfort (IMAC) for naturally ventilated buildings (Manu *et al.*, 2016) using the following equation.

$$\text{Neutral temp.} = 0.54 \times (\text{30-day outdoor running mean air temperature}) + 12.83 (\pm 2.4^\circ\text{C})$$

Indoor air temperatures were also assessed against the ASHRAE-55 adaptive model 90% acceptability range using the following equation:

$$\text{Neutral temp.} = 0.31 \times (\text{30-day outdoor running mean air temperature}) + 17.8 (\pm 2.5^\circ\text{C})$$

Outdoor air temperature observations had two missing data sequences that were completed using linear interpolation as shown in Figure 4.

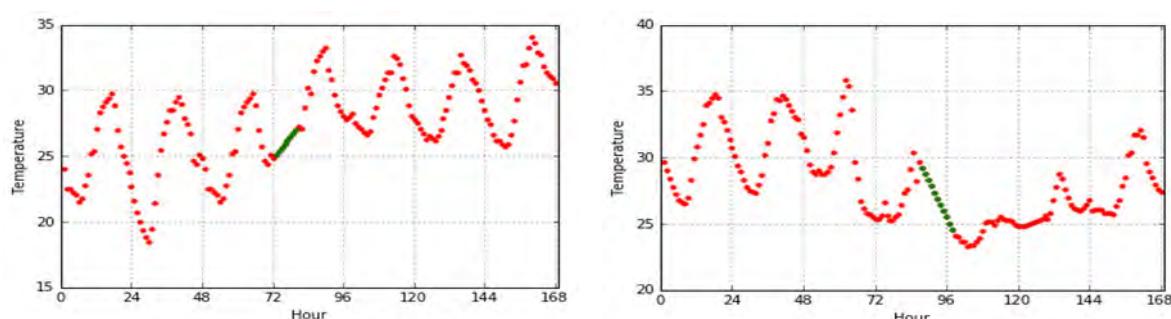


Figure 4 Missing outdoor temperature sequences one and two, and the interpolated values

Figures 5 and 6 show the heat maps indicating the status of comfort (based on IMAC-NV and ASHRAE-55 models) for every hour of the monitoring period for all spaces in each of the 10 houses. The grey bands show the days when the 30-day outdoor running mean air temperature values fell outside the range of 12.5–31°C in the case of IMAC- NV and 10–33.5°C in the case of ASHRAE-55 adaptive models. These days or hours were excluded from the analysis. Indoor air temperatures lying within the 90% acceptability range were used to calculate the number of comfortable hours whereas those falling outside of this range were deemed uncomfortable. The x-axis depicts the date and time, starting from 11 August 2015, 00:00 hours to 13 May 2016, 23:00 hour, making a total of 6648 hours indicated as vertical columns on the heat map. Each observed space is plotted on the y-axis. White cells indicate missing data.

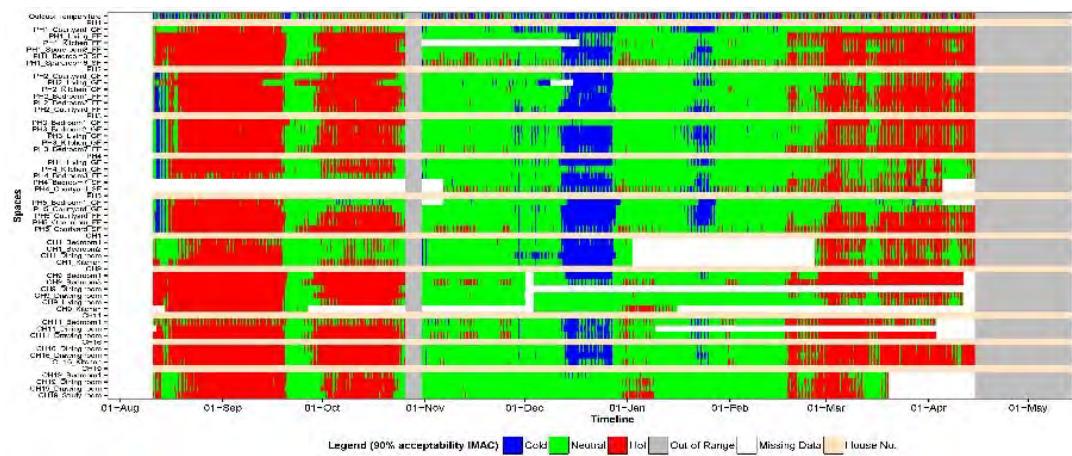


Figure 5 Heat map as per IMAC showing 90% acceptability range

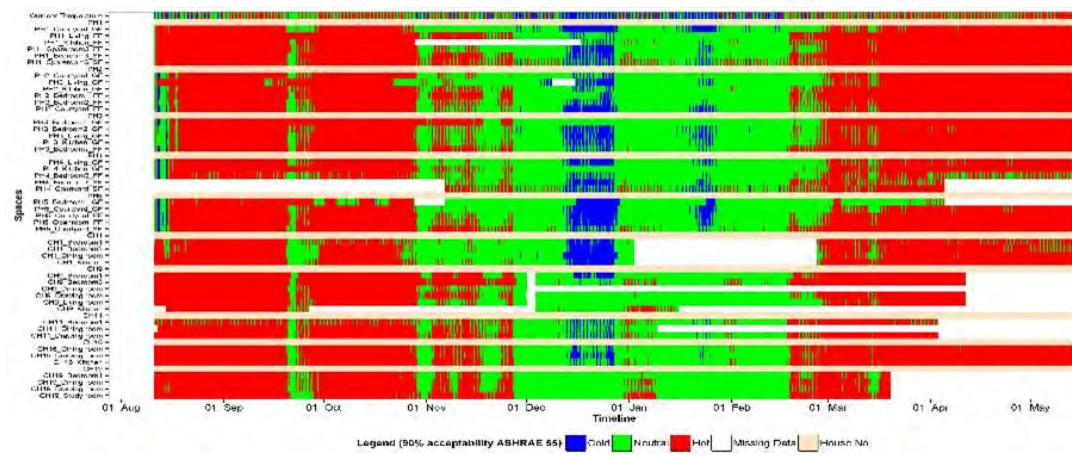


Figure 6 Heat map as per ASHRAE 55- 2013 showing 90% acceptability range

The percentage of comfortable hours (out of a total of 6648 hours of observations) was calculated for each space in PH and CH based on the IMAC-NV and ASHRAE-55 models. The results are plotted in Figures 7 and 8. Green bar in on the left in these figures shows the percentage of comfortable hours lying within 90% acceptability range of IMAC and ASHRAE-55 for outdoor temperature. So, in terms of outdoor temperature, 35% of hours were deemed comfortable according to the IMAC model and 40% according got the ASHRAE-55 model. The different bars within a house category show the spaces that were monitored. With respect to IMAC as reference, availability of data and averaging all spaces, CH19 is house with 57.1%

comfortable hours followed by PH4 (55.2%), PH5 (48.4%), CH1 (47.1%), PH2 (47%), PH3 (46.3%), CH11 (42%), CH9 (41.7%), CH16 (41.3%) and PH1 (40.5%). However it is to be noted that considerable variation within the same house case of PH1, PH4, PH5, and CH9. It was found that the courtyard spaces in PH1 and PH2 were the most comfortable compared to other spaces in these houses. CH19 is the only house where all spaces report greater than 50% comfortable hours on the basis of the IMAC model (Figure 7).

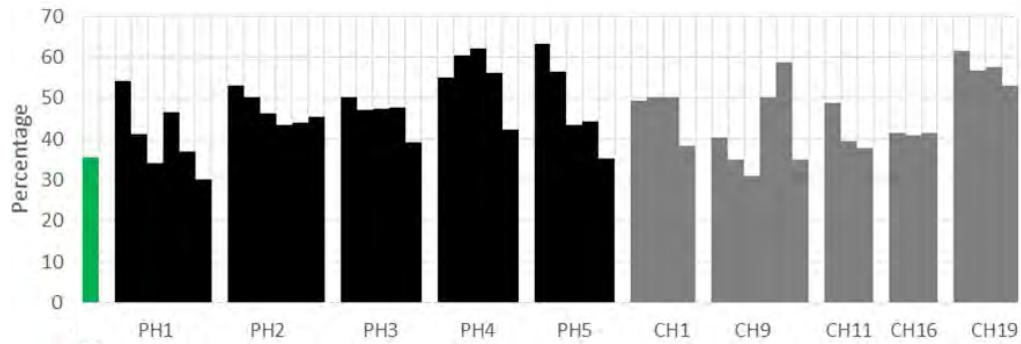


Figure 7 Total comfortable hours in percentage for each space as per IMAC

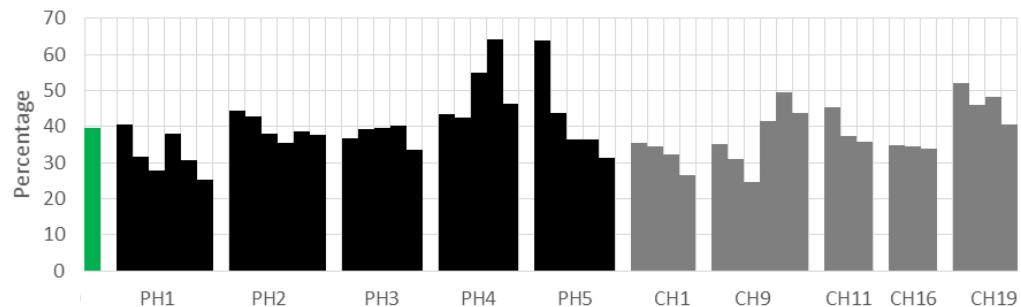


Figure 8 Total comfortable hours in percentage for each space as per ASHRAE-55 Adaptive Model

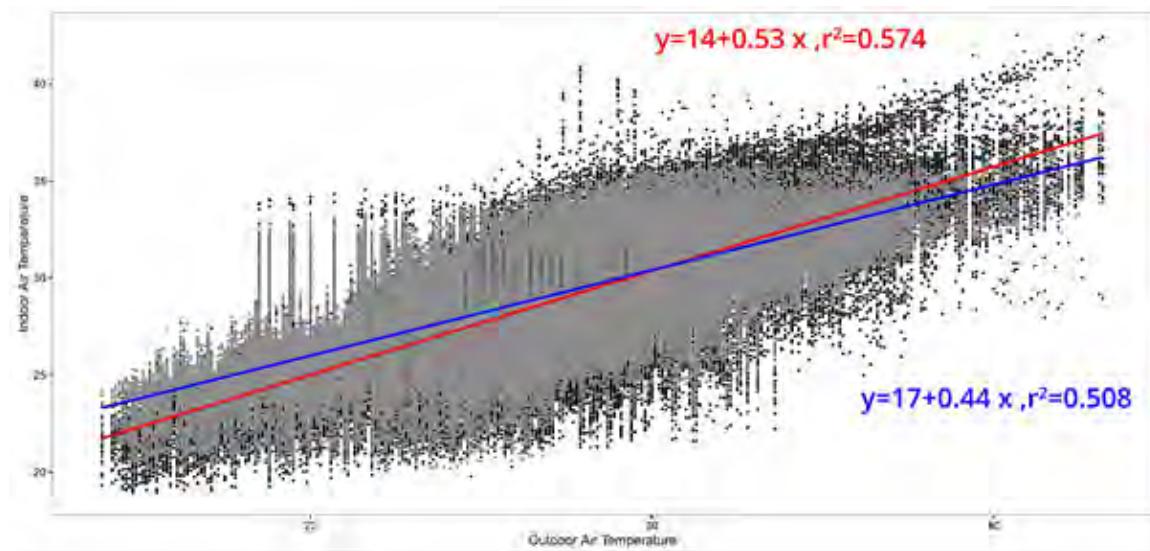


Figure 9 Correlation between Outdoor and Indoor Air Temperature in *pol* and contemporary houses

As observed in the Figure 9, the relationship between indoor air temperature and outdoor air temperature for *pol* houses and contemporary houses is quite similar and moderately strong ( $R^2 \approx 0.5$ ). Indoor temperatures for *pol* houses are indicated as black

colored scatter points while those for contemporary houses are in grey. The red colored linear regression line indicates the relationship between temperatures inside *pol* houses and outdoor temperatures. The blue regression line is for contemporary houses. The intercept value in the expression for contemporary houses is higher by 3°C than that of the *pol* houses. On the other hand, the slope of the regression line is slightly steeper for *pol* houses.

## Conclusion

Based on the analysis presented in this study, it is difficult to determine with of absolute certainty whether one dwelling type is better than the other is. When viewed in terms of the relationship between outdoor and indoor conditions, it seems that the *pol* houses have a marginally faster response to outdoor conditions. That is counterintuitive to the traditional knowledge and the qualitative literature about this form of vernacular architecture where thermal mass has been exalted as one of the most important passive strategies to keep the heat out. These houses are mutually shaded as well which ensures that only the roof is exposed to direct radiation. Even that is limited by reducing the roof area by distributing the total area vertically on several floors. The contemporary houses, on the other hand, are lighter in mass and have larger floor plates. To arrive at definite conclusion authors feel that peak summer conditions should also be studied. It is very important to understand the effect of roof on indoor conditions and thermal comfort.

## Acknowledgement

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## References

- ASHRAE (2013) *ANSI/ASHRAE Standard 55-2013 - Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating and Air-Conditioning Engineers, Inc.
- Bajracharya, S. B. (2014) 'The Thermal Performance of Traditional Residential Buildings in Kathmandu Valley', *Journal of the Institute of Engineering*, 10(1), pp. 172–183. Available at: <http://www.nepjol.info/index.php/JIE/article/viewFile/10898/8872>.
- Bureau of Indian Standards (2005) *National Building Code of India 2005*. Edited by M. Kisan, S. Sangathan, J. Nehru, and S. G. Pitroda. New Delhi: Bureau of Indian Standards.
- Census of India 2011 (2011) *Primary Census Abstract - Data Highlights, Primary Census Abstract*. Available at: [http://www.censusindia.gov.in/2011census/PCA/pca\\_highlights/pe\\_data.html](http://www.censusindia.gov.in/2011census/PCA/pca_highlights/pe_data.html).
- IEA, I. E. A. (2015) 'India Energy Outlook', *World Energy Outlook Special Report*, pp. 1–191.
- Kundu, A., Mohanty, P. K., Kumar, S., Chandramouli, C., Pethe, A., Mohanan, P. C., Risbud, N., Gupta, S., Das, Mahadevia, D., Verma, R. V. and Negi, D. S. (2016) *Report of the Technical Group on Urban Housing Shortage (TG-12) (2012-17)*. New Delhi, India. Available at: <http://www.nbo.nic.in/Images/PDF/urban-housing-shortage.pdf>.
- Mahadevia, D., Desai, R. and Vyas, S. (2014) *City Profile: Ahmedabad*. Ahmedabad, India.
- Manu, S., Shukla, Y., Rawal, R., Thomas, L. E. and de Dear, R. (2016) 'Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC)', *Building and Environment*, 98, pp. 55–70. doi: 10.1016/j.buildenv.2015.12.019.
- Matthews, J. (2000) *Thermal comfort in the havelis of Jaisalmer*. University of East London. Available at: <http://roar.uel.ac.uk/1252/>.
- Philokyprou, M., Michael, A., Malaktou, E. and Savvides, A. (2017) 'Environmentally responsive design in Eastern Mediterranean. The case of vernacular architecture in the coastal, lowland and mountainous regions of Cyprus', *Building and Environment*, 111, pp. 91–109. doi: <https://doi.org/10.1016/j.buildenv.2016.10.010>.
- Priya, R. S., Sundarraja, M. C. and Radhakrishnan, S. (2012) 'Comparing the thermal performance of traditional and modern building in the coastal region of Nagappattinam, Tamil Nadu', *Indian Journal of*

*Traditional Knowledge*, 11(3), pp. 542–547. Available at:  
[http://nopr.niscair.res.in/bitstream/123456789/14399/1/IJTK\\_11%283%29\\_542-547.pdf](http://nopr.niscair.res.in/bitstream/123456789/14399/1/IJTK_11%283%29_542-547.pdf).

Rashid, R. and Ahmed, M. H. Bin (2013) 'The Comparison Between The Thermal Performance of a Contemporary House and Traditional House in the Dense Dhaka City in Bangladesh', *DIMENSI - Journal of Architecture and Built Environment*, 40(1), pp. 11–18. Available at:  
<http://dimensi.petra.ac.id/index.php/ars/article/view/18795>.

Sangkertadi, S., Syafriny, R. and Tungka, A. E. (2008) 'Thermal Comfort Comparison of Traditional Architecture and Modern Style Housing in North Sulawesi - Indonesia', in *Humanity + Technology: Proceedings 9th SENVAR + 2nd ISESEE 2008*. Kuala Lumpur, Malaysia: Pusat Penerbitan Universiti, Universiti Teknologi Malaysia.

Selvanathan, S. P. and Migdalska, J. (2015) 'Cooling Degree day analysis as a climate impact indicator for different location of Poland and India', *International Journal of Advances in Science Engineering and Technology*, (4), pp. 43–51. Available at: [http://www.iraj.in/journal/journal\\_file/journal\\_pdf/6-222-145431937543-51.pdf](http://www.iraj.in/journal/journal_file/journal_pdf/6-222-145431937543-51.pdf).

Shastry, V., Mani, M. and Tenorio, R. (2016) 'Evaluating thermal comfort and building climatic response in warm-humid climates for vernacular dwellings in Sugenghalli (India)', *Architectural Science Review*, 59(1), pp. 12–26. doi: 10.1080/00038628.2014.971701.

Shukla, Y., Bansal, N. K. and Rawal, R. (2012) 'Comfort and Weather Analysis Tool'. Ahmedabad, India: Centre fOr Advanced Research in Building Science and Energy, CEPT University. Available at: <http://www.carbse.org/resource/tools/>.

Shukla, Y., Shnapp, S. and Rawal, R. (2015) 'Residential buildings in India: Energy use projections and savings potentials', in Lindström, T. L. (ed.) *ECEEE 2015 Summer Study - First Fuel Now*. Toulon/Hyères, France: European Council for an Energy Efficient Economy, pp. 1193–1206.

Subramanian, C. V., Ramachandran, N. and Kumar, S. S. (2016) 'Comparative Investigation of Traditional, Modern and Designed Solar Passive Building for Thermal Comfort in Thanjavur', *International Journal of Innovations Engneeng and Technology*, 7(2), pp. 283–291. Available at: <http://ijiet.com/wp-content/uploads/2016/08/43.pdf>.

Subramanian, C. V., Ramachandran, N. and Kumar, S. S. (2017) 'Performance Evaluation of Traditional and Modern Residential Budings for Thermal Comfort by Questionnaire Survey in Thanjavur', *International Joural of Civil Engineering and Technology (IJCET)*, 8(2), pp. 440–451. Available at: [https://www.iaeme.com/MasterAdmin/uploadfolder/IJCET\\_08\\_02\\_047/IJCET\\_08\\_02\\_047.pdf](https://www.iaeme.com/MasterAdmin/uploadfolder/IJCET_08_02_047/IJCET_08_02_047.pdf).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Climate change scenarios analysed with the transient energy ratio

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**Abstract:** While thermal resistance and conductance are well understood, and their effect on a building's energy use easily quantified – often with the use of the U-value parameter – the effects of thermal mass are understood only poorly, if at all. In the literature there is much vague commentary on the benefits of thermal mass, but little by way of solid analysis. Two parameters, the transient energy ratio and effective U-value, quantify the effect of thermal mass on energy use. These parameters measure the divergence in performance between a high- and low- thermal mass wall under equivalent conditions. Previous work has shown disadvantages to the use of thermal mass in northern European climates; during the heating season, high thermal mass structures cause an increase in energy use. This paper examines how the influence of thermal mass on energy use might alter once climate change is considered. The work uses the transient energy ratio to look at the performance of various wall typologies under climate change scenarios for a range of locations and occupancy patterns.

**Keywords:** Thermal mass, climate change, UK, overheating, thermal storage

### The Changing Climate

The IPCC scenario for medium emissions predicts a global mean temperature rise of around 4 K by 2100 (IPCC). This rise will not be evenly distributed, with both seasonal and spatial variation; variation within the UK is given in DEFRA PB13274. The UK has already experienced a mean temperature rise of about 1 K since 1970, with wetter winters and drier summers.

Much of the predicted rise for the remainder of this century could be avoided, but due to the increased impact of early emissions significant reductions would have to be made very soon in order to meet the IPCC's low emissions scenario. However, the prioritisation of short-term economic gain over longer-term impacts means that the probability of keeping emissions below even the envisioned medium scenario is low.

Assuming that the medium scenario is the one which comes to pass, many regions – including much of the UK – will see hotter summer temperatures. Consequently, a greater increase in the use of air conditioning, especially in commercial buildings, is likely. Table 1 gives mean summer temperatures between the hours of 9am and 5pm, along with the proportion of hours that the outside temperature exceeded 299.15 K (26 C), for 2015 and 2080. This arbitrary limit is chosen as it is the CIBSE guide A threshold temperature for overheating in bedrooms; this limit appears to be more stringent than other proposed criteria, such as the TM52 criteria, under climate change scenarios (Braham et al, Bhaumik).

The figures in Table 1 show that, while present-day outdoor temperatures in the UK very rarely exceed 26 °C, by 2080 even cities such as Belfast, Glasgow and Edinburgh will

have substantial periods where the outside air temperature exceeds this limit. Indoor temperatures will be higher still, especially in commercial buildings given the current fashion for large expanses of glazing, and the high internal gains that occur in heavily-occupied spaces. Consequently, it seems likely that the use of air-conditioning will become much more prevalent, with an attendant increase in energy use.

Table 1. Weather statistics for summer (Jun, Jul and Aug). Data from the UK Met Office. (2015 was slightly below the 1981 – 2010 average with Jun, Jul and Aug mean temperatures 0.3, 0.7, 0.2 K lower. Further work will model a wider range of temperatures.)

Location	2015 (measured)			2080 (estimated)		
	Mean summer temperature		Total time temperature exceeds 26°C	Mean summer temperature		Total time temperature exceeds 26°C
	K	°C	Hours	K	°C	Hours
Coleshill	291.6	18.4	18	295.9	22.7	107
Glasgow	288.6	15.4	3	292.9	19.7	23
Cambourne	287.9	14.7	0	293.7	20.5	9
Scilly St Mary's	289.7	16.5	0	294	20.8	0
Belfast	288.8	15.6	0	293.1	19.9	15
Dublin	286.1	12.9	0	292.6	19.4	14
Edinburgh	289.2	16	0	293.5	20.3	17
Linton-on-Ouse	291.1	17.9	14	295.4	22.2	86

## Thermal Mass

Regarding insulation levels, many professional bodies and national guidelines produce detailed, quantitative standards for the required insulation levels in buildings, and in many countries these standards have legal backing (e.g. in the UK, the Building Regulations 2016). However, guidelines for thermal mass are much less robust, such as the guidance from the Royal Institute of British Architects: “[Insulate] the thermal storage from exterior climate conditions, so that they do not add or remove too much heat”. This raises the questions: How much is too much? How much insulation is required? The general assumption in many guides is that thermal mass is always good (quoting again from RIBA: “There is no upper limit for the amount of well-designed thermal mass”). Unfortunately, the scientific basis for the use of thermal mass is relatively weak, and it remains a poorly understood topic. In part, this is due to the more complicated nature of dynamic interactions compared to steady-state analysis: while increasing insulation levels in a building are almost always beneficial, the effect of increasing thermal mass can be positive or negative (Tsilingiris 2006, Reilly and Kinnane 2016 and 2017a). Understanding which is more difficult, as a dynamic analysis depends on how the heat capacity interacts with the indoor and outdoor temperature profiles, the building occupancy pattern and the heating/cooling and ventilation strategies employed.

Thermal mass is generally accepted as being of most benefit in climates where there is a wide diurnal temperature range. It clearly has a moderating influence over temperatures when buildings are in a ‘free-running’ case, i.e. without active heating/cooling systems; and several studies support its potential to reduce energy demand in hot climates (for example Karlsson et al 2013, Kosny and Kossecka 2002, Kossecka and Kosny 2002, Carlos 2016). However, in cases where active heating is employed, thermal mass can cause an increase in energy consumption (Tsilingiris 2006, Reilly and Kinnane 2016); and in a climate where building energy consumption is dominated by heating – such as that of northern Europe – thermal mass most often causes an increase in energy use rather than a decrease (Reilly and

Kinnane, 2017a). Thermal mass is generally a drawback in the UK at present as regards energy use, due to the long heating season (Reilly and Kinnane 2016, 2017a, 2017b). In a hotter climate such as that to come by the end of the century, the effects of thermal mass are less certain; it is possible that energy savings in summer outweigh the drawbacks in winter.

### The Transient Energy Ratio Method

The transient energy ratio method is a method to quantify the heat storage properties of walls, in respect of their influence on the indoor temperature. This method is described in detail in Reilly and Kinnane, 2017a.

A key feature of the TER method is its abstraction of the wall element from any particular building. In this way, the effects of thermal mass can be isolated and studied independently of any assumptions about the particular building in which they will be used. This allows robust conclusions to be developed about the relationship between wall typology and indoor environment; the conclusions are therefore of interest for buildings where heat flow through the walls makes a significant contribution to the overall heat balance.

In summary, the procedure is as follows (from Reilly and Kinnane 2017b):

- Calculate the U-value for the wall section in question (termed U)
- Dynamically simulate the thermal behaviour of the wall, using boundary conditions representative of the climate and indoor occupancy pattern of interest (typically at least a week is required to get an accurate representation, here, several months of data are used)
- Use the actual energy flow through the wall in the dynamic simulation to calculate an effective U-value (termed  $U_e$ )
- Divide  $U_e$  by U to find the transient energy ratio (TER)

The dynamic simulation is necessary to capture the true behaviour of the walls. In conditions of changing surface temperatures, heat may be stored and returned to the indoor and outdoor environment: this is the basis of thermal mass. A dynamic simulation attempts to capture these effects by modelling the response of a wall to varying temperatures. The effective U-value is the quantity which, when used with the mean temperatures, gives the actual energy flow through the wall.

This actual energy flow may be greater or less than that predicted based on the static U-value, and this ratio is termed the TER. If the TER is less than one, the thermal mass of the wall offers energy savings, over and above any savings purely due to a low conductivity. On the other hand, if the TER is greater than one, the wall is leading to greater energy use than predicted by a static analysis.

#### *Static Analysis*

The static analysis was simply an evaluation of each wall's U value, calculated in the standard manner as in Eqn. 1 below (where L is the thickness of each material, k is the conductivity, and the subscript indicates the material).

$$1/U = L_1/k_1 + L_2/k_2 + \dots + L_n/k_n \quad (1)$$

#### *Dynamic Analysis*

The principle of the TER method is to use a dynamic simulation of a wall section. To comply with the method, any simulation method that accurately predicts internal wall temperatures may be used. For this work, a finite element (FE) model was created using commercial FE software (Abaqus 6.12). The walls were modelled using heat transfer elements with a typical mesh dimension of around 1 mm, and the increment time in the

model was set such that in no step did the temperature change exceed 0.1 K. Heat transfer at the wall surfaces was modelled according to ISO 6946, as in Eqn. 2 below. (Where  $\bar{v}$  is the mean wind speed,  $\epsilon$  the emissivity,  $\sigma_0$  the Stefan-Boltzman constant and  $T_0$  the relevant environmental temperature.)

$$h = 4 + 4\bar{v} + 4\epsilon\sigma_0 T_0^3 \quad (2)$$

Solar flux was applied to the outside face as a power input per unit area. The output from the model, is a heat flux on the interior surface of the wall ( $\text{W m}^{-2}$ ). This average heat flux per unit area was divided by the mean temperature difference to give the effective U-value. In this way, the effective U-value accurately reflects the heat loss/gain through the wall, but has units of  $\text{W m}^{-2}\text{K}^{-1}$ , making it directly comparable with the standard U-value calculated through a static analysis.

### Scenarios

This paper compares two pairs of wall types; within each pair, the walls have identical U-values but different heat capacities, giving different dynamic thermal characteristics. The first pair of walls were chosen to represent extremes of heat capacity, rather than being directly representative of actual construction; one of these was made entirely of blockwork, and the other, entirely insulating material. The insulating wall was 100 mm thick, the blockwork wall 800 mm. These both had a U-value of 0.55; these values were chosen as extreme cases of high and low heat capacity. This led to higher U-values than would be typical of new construction, but this is a compromise to best illustrate the effects of thermal mass. (Blockwork was chosen rather than brickwork, or natural stone, as the higher conductivity of stone and brick would require a wall a few meters thick to match the U-value of even 100 mm of low-quality insulation.)

The second pair of walls were much more representative of modern construction: these consisted of multilayer walls with masonry, plaster, render and insulation, with a U-value for both of  $0.16 \text{ W m}^{-2}\text{K}^{-1}$ . This value is often taken as the target U-value for well-insulated or passive construction. The difference between these two walls was the order of the layers: in the first case, the insulation layer was inside the main structural layer, in the second, the insulation layer was outside the main structure. Consequently, although these two walls both had identical U-values and (total) heat capacities, the dynamic response was different due to the order of the layers. Wall details are given in Table 2.

Three outside environments were modelled for each wall: winter 2015 to 2016, summer 2015, and summer 2080. (An improvement, intended for future work, is to use more accurate representative data, such as that suggested in Eames et al., 2011.)

Table 2. Wall construction details: wall A is as described below, wall B is the same but with the brick and insulation layers swapped round. Material properties from Clarke (1990).

Material	Thickness (mm)	Conductivity ( $\text{W m}^{-1}\text{K}^{-1}$ )	Density ( $\text{kg m}^{-3}$ )	Specific heat ( $\text{J kg}^{-1}$ )
Plaster	25	0.52	1300	840
Insulation	332	0.055	320	99
Brick	102	0.721	1920	796
Render	25	0.7	1100	900

Of course, the environmental control strategy employed is critical to the actual energy consumption. (Hereafter, this will be referred to as the 'heating strategy' for brevity, although this encompasses active heating, active cooling, and free ventilation.) Although often receiving less attention than construction details, the heating strategy has a greater effect on overall energy consumption; and it is even more important to consider the effects

of heating strategy in a thermal mass study. One heating strategy is modelled for winter: this is a setpoint temperature of 294 K (21 °C) between the hours of 9am and 5pm (corresponding to a typical office). Three heating strategies are modelled during summer: (1) a free-running, air-tight building; (2) a building that is air-tight between 6am and 6pm with forced internal ventilation using outside air between 6pm and 6am; and (3) air-tight with active cooling and a setpoint of 294 K between 9am and 5pm.

## Results

### ***Theoretical very high and very low thermal mass walls***

The results of the dynamic modelling are expressed in terms of the effective U-value ( $U_e$ ) and the transient energy ratio (TER). This facilitates comparison with the conventional U-value calculated directly from the conductivity of each wall, and the TER thus illustrates the benefit or drawback associated with the thermal mass in each case.

Starting first with the winter case, comparing the walls made entirely of blockwork and insulation: in this case, the TER of the insulation wall is 1.17. This is close to unity, which indicates that the thermal mass of this wall contributes little to its performance. This is as expected: the thermal mass of this ‘wall’ is very low. However, that is not the case for the blockwork wall: this wall has a very high TER of 3.2. These results translate into the effective U-values shown in the table: while the insulation performs close to the way it would based purely on studying the U-value,  $U_e$  for the blockwork wall is 1.78. When used under these conditions, the thermal mass of the blockwork wall is a very significant drawback: the blockwork wall performs, not like an insulation layer of 100 mm, but like an insulation layer of only 31 mm. The blockwork wall draws so much heat out of the room at the start of each heating period that the energy consumption is dramatically increased, and although a proportion of that heat is returned to the room at the start of the next heating period, the majority is lost to the environment outside occupied hours.

However, during summer (of 2015), the case is very different. In the summer free-running case, the temperature of the insulation ‘wall’ tracks the outside temperature much more closely than does the blockwork wall. In this case, the dynamic properties and heat storage capacity of the blockwork wall effectively buffer the temperature changes from the outside environment. The inside temperature of the blockwork wall remains much more constant, not once rising above 296 K. For summer use in the UK, it appears that thermal mass is generally beneficial, and for most uses a high thermal mass building produces an environment that has a more constant temperature and is probably more pleasant. The high mass structure is not cooler on average: the two structures have identical mean temperatures (of 292 K, or 19 C, in Birmingham). This is a classic example of a scenario where thermal mass is useful, such as its traditional use in mediterranean climate zones.

### ***Multilayer walls***

The second part of the study looks at more realistic wall typologies, modelled for the same time periods. A previous study (Reilly and Kinnane, 2017a) found that, with heavily insulated walls such as these, the greatest performance in winter is found by having the insulation layer inside the structural, high-heat-capacity layer: the TER of the wall with the insulation on the outside was 3.7, as opposed to 3.1 for the wall with insulation on the inside. A lower TER is better, and this difference represents approximately 20% extra energy that was lost through the walls with external insulation. This is because thermal mass, in typical winter conditions in northern Europe, is a drawback: most of the heat that is stored in the walls

comes from the heating system, and much of this heat is returned to the indoor space outside occupied hours, when it is of no benefit. Consequently, the heating system has to provide more energy overall to maintain acceptable conditions during occupied hours. However, as many studies have shown the benefit of thermal mass during summer, is there a trade-off to be made?

First of all, the walls were modelled under free-running, air-tight conditions. A sample image is shown in Figure 1. This shows a very definite benefit of thermal mass: for the wall with insulation on the outside, the indoor temperatures are much more steady. The indoor surface temperature for wall A exceeds 299 K (26 °C) for 28% of the summer, while for wall B, this point is never exceeded.

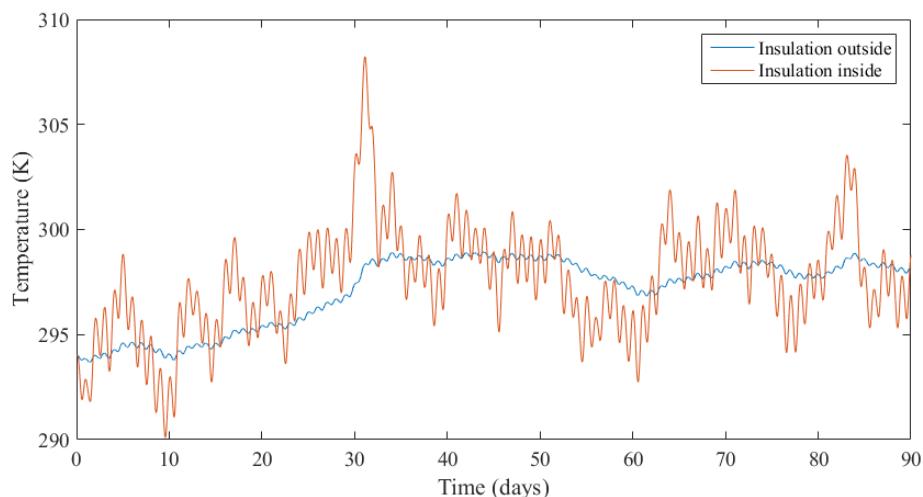


Figure 1. Indoor wall surface temperatures under free-running conditions, during June, July and August 2080. Temperatures shown for Coleshill, Birmingham, UK.

Although wall B never rises above the 299 K threshold, there may still be a requirement for air conditioning and active cooling – for example, in densely-occupied offices, or other buildings with high internal gains. This scenario can be examined with the TER, once more.

Figure 2 shows the wall surface temperatures for a typical ten day period. Both walls have a temperature very close to the setpoint during occupied hours; outside occupied hours the temperature of the wall with insulation on the inside rises much more; but, as the building is unoccupied, the temperature during this period is not of great interest and the heat could be removed using a night ventilation strategy. During occupied hours the indoor conditions in the two walls are essentially identical. What is of greater interest, is the energy required to maintain these conditions. The heat flux through the two walls is shown in Figure 3. Although the peak heat flux is greater for wall A, the total energy inflow – the area under the curve – is greater for wall B.

The energy flow through the wall is the energy that needs to be removed from the indoor space by the air-conditioning unit. Taking into account the total energy outflow over the whole summer, the TER for wall B is 0.78, but for wall A, only 0.51. These can be converted into effective U-values, as shown in Table 3.

Table 3. Effective U-values and transient energy ratios. Wall A has insulation on the inside, wall B has insulation on the outside.

Wall	Static U-value $\text{W m}^{-2} \text{K}^{-1}$	TER (winter heating)	$U_e$ , winter $\text{W m}^{-2} \text{K}^{-1}$	TER (summer cooling)	$U_e$ , summer $\text{W m}^{-2} \text{K}^{-1}$
A	0.16	3.1	0.50	0.51	0.08
B	0.16	3.7	0.59	0.78	0.12

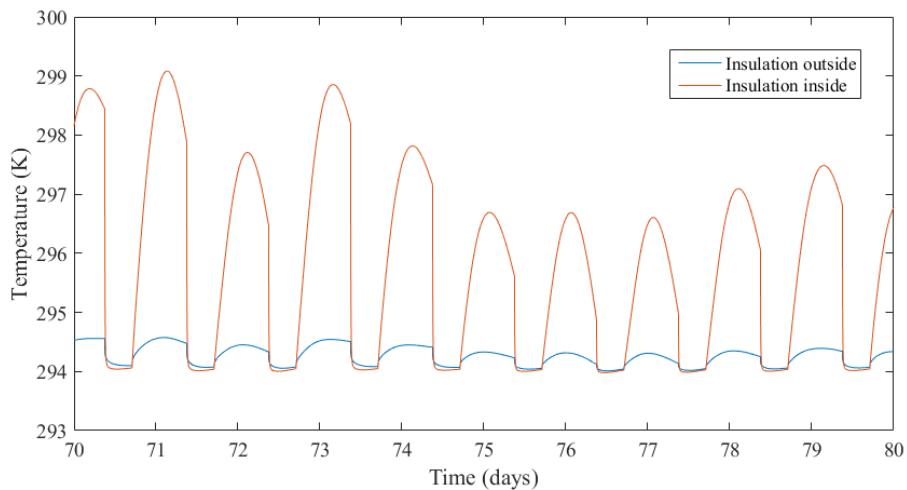


Figure 2. Indoor wall surface temperatures with active cooling (to 294 K) during 9am to 5pm, for ten days in August 2080 for Coleshill, Birmingham, UK.

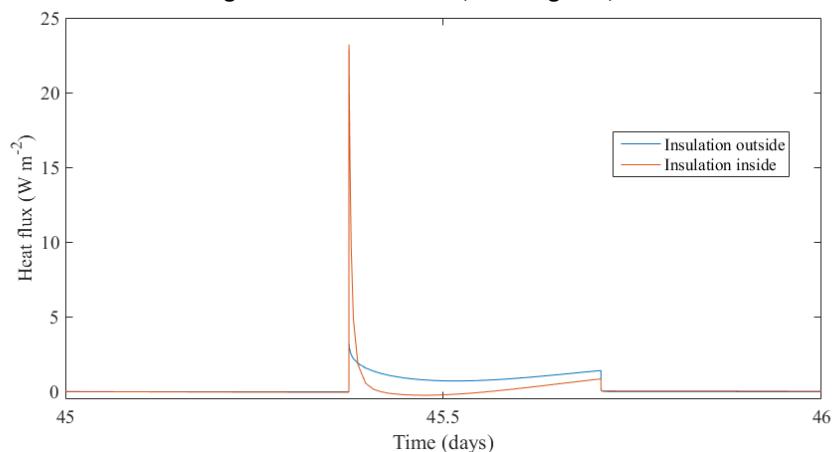


Figure 3. Wall heat flux (indoor face) for the conditions in Figure 2.

## Discussion

The results for Birmingham are presented here as that was the location with the greatest proportion of time with an outdoor temperature in excess of 26 °C (299 K): 18 hours during the summer of 2015. In most buildings in the UK, at present, it ought to be possible to eliminate overheating without the use of air-conditioning. However, this will likely change substantially by 2080. Once the effects of solar gain are included, heat flow through even well-insulated walls will be sufficient to cause significant periods of overheating (by the same criterion). Insulation standards may improve by then, but many buildings under construction today will still be around by 2080, so it is instructive to use examples that are currently considered best practice.

Figure 1 shows the effect that thermal mass can have in reducing overheating, and it is indeed dramatic. By placing the masonry layer inside the insulation instead of outside, overheating (by one criterion) is eliminated with this construction element. The maximum temperature reached over the summer of 2080 is 0.05 K below the threshold, so in this sense the heat capacity of this wall is perfectly matched to the climactic conditions for Birmingham (and the rest of the UK is similar). However, this comes at a cost: the energy used for winter heating increases, and by around 20% this increase is far from insignificant. There is a balance to be struck between the optimum winter configuration and the optimum summer configuration. Under the conditions assumed for this study, it is likely that the cost

savings of avoiding air-conditioning plant (by increasing the effective thermal mass) would be greater than the cost savings related to lower winter energy use (achieved by reducing thermal mass).

In some cases, air-conditioning might be installed anyway. Internal gains might be significant; the history of architecture shows a trend towards ever more tightly-controlled indoor environments, so future client expectations might be more demanding. Buildings that are built today, without air-conditioning, might be retrofitted to include it. In which case, the use of thermal mass seems much less advisable. Many guidelines today make recommendations to include thermal mass wherever possible in buildings, assuming that it is always beneficial, but this should not be the case. Where buildings are free-running, thermal mass does indeed moderate indoor temperatures. However, once control is passed to a mechanical system, this advantage disappears, since the mechanical system takes over the task of maintaining temperatures. With active heating/cooling in place, the objective becomes one of providing given indoor conditions at minimum energy use – and in this role, thermal mass is generally a drawback. There are some cases where it can be useful (such as climates with very large diurnal temperature variation), but in the main, these tend to be the outliers. For northern Europe, the use of thermal mass needs to be examined much more carefully, and blanket recommendations to include as much thermal mass as possible do not appear to have a sound theoretical basis.

## References

- Bhaumik, C.L. Das (2014). A comparison of overheating criteria for a range of building types. In: *CIBSE ASHRAE Technical Symposium*, Dublin, Ireland, 3-4 April 2014
- Braham, D. et al eds (2007). *CIBSE Guide A: Environmental Design*, 7<sup>th</sup> Ed. Issue 2. London, UK: CIBSE Publications
- Building Regulations (2016). *Building Regulations, Approved Document L: Conservation of Fuel and Power*. Department for Communities and Local Government (United Kingdom)
- Carlos, J.S. (2016). The impact of thermal mass on cold and hot climate zones of Portugal. *Indoor and Built Environment*, Online first, DOI: 10.1177/1420326X16635237
- Clarke, J.A. et al (1990). *The Harmonisation of Thermal Properties of Building Materials*. Building Research Establishment BEPAC Report. Walford, UK: Building Research Establishment.
- Eames, M., Kershaw, T. and Coley, D. (2011). On the creation of future probabilistic design weather years from UKCP09. *Building Serv. Eng. Res. Technol.* 32(2) pp. 127–142
- IPCC (2014). R.K. Pachauri and L.A. Meyer (eds.), *Synthesis Report: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, 151 pp.
- Karlsson, J., et al (2013). A conceptual model that simulates the influence of thermal inertia in building structures. *Energy and Buildings*, 60, 146-151.
- Kosny, J. and Kossecka, E. (2002). Multi-dimensional heat transfer through complex building envelope assemblies in hourly energy simulation programs. *Energy and Buildings*, 34(5), 445-454.
- Kossecka, E. and Kosny, J. (2002). Influence of insulation configuration on heating and cooling loads in a continuously used building. *Energy and Buildings*, 34(4), 321-331.
- DEFRA PB13274: UK government Department for Environment, Food and Rural Affairs, Adapting to Climate Change; *UK Climate Projections*, Document Number PB13274
- Tsilingiris, P.T. (2006). Wall heat loss from intermittently conditioned spaces—The dynamic influence of structural and operational parameters. *Energy and Buildings*, 38(8), 1022-1031
- Reilly, A. and Kinnane, O. (2016). A parameter for quantifying the transient response of walls to dynamic thermal loading. In: *Advanced Building Skins*, Bern, Switzerland.
- Reilly, A. and Kinnane, O. (2017a). The Impact of Thermal Mass on Building Energy Consumption. *Applied Energy*, in press, accepted for publication 08/04/17.
- Reilly, A. and Kinnane, O. (2017b). An Assessment of the Thermal Storage Capacity of Hemp-Lime Using the TPR Method. *In Press*.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Cluster analysis for thermal behaviour assessment of low-income housing

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**Abstract:** In order to provide low-energy buildings, it is necessary to identify their main existing energy-related architectural features. This research aims to clusterize a sample of houses according to their thermal performance and find the main architectural features of each cluster. The method involves obtaining data, computer simulation and cluster analysis. Data for 102 low-income single-family houses were summarized to form a database for the following steps. Each house was subjected to computer simulation, from which the long-term room operative temperatures were obtained. Cluster analysis was applied to group houses with similar performances. Finally, each cluster was described according to its features to find those that affected each cluster performance. Three clusters were found: worst, best and intermediate performance. The cluster with the worst performance was mainly composed of smaller houses made of wood walls and no slab on the roof, with combined living room and kitchen. The cluster that had the best performance was composed of larger houses made of ceramic bricks, concrete slab on the floor, and ceramic tiles and wooden lining in the roof. It was possible to conclude that the architectural features of those houses can significantly influence their performance, particularly those related to size and fabric.

**Keywords:** Thermal performance of buildings, clustering, low-income housing, computer simulation

### Introduction

Buildings are responsible for 40% of the world energy expenditure, of which the residential sector accounted for about 30% (IEA, 2012). In Brazil, buildings were responsible for 48% of the total energy consumption, and the residential sector accounts for 24% (MME, 2015). Energy consumption in buildings depends on many factors. In the residential sector specifically, many studies have shown that energy consumption is strongly related to the use of air-conditioners (McNeil and Letschert, 2010; Fracastoro and Serraino, 2011), revealing the bad thermal performance of the building (Bodach and Hamhaber, 2010). Fostering more efficient buildings also depends on government actions, starting from the development of standards and guidelines to properly guide the professional decision at the time of design and construction of new buildings, which have motivated governments to support studies on energy efficiency in buildings. Strategies to decrease energy consumption should be thought on a global level, and their success depends on the features related to the energy consumption of an entire stock (Dascalaki et al., 2010). A building stock is composed of buildings with different features and therefore they have different performances; thus different strategies should be applied.

One way to separate the stock into groups with similar features is through the application of cluster analysis. Cluster analysis is a tool for pattern identification, which aims to find homogeneity between objects of the same group and heterogeneity between objects

of different groups (Hair et al., 2009). Having a sample of buildings divided into groups with similar features allows to assess the performance of each group separately, to draw a profile and then to develop specific strategies of energy efficiency for each group.

In Brazil, the increasing development of public policies for low-income housing is expected to contribute in reducing the housing deficit, and that will certainly cause impacts on energy demand. The residential sector, particularly low-income housing (due to its large deficit), is therefore an important area for research on energy efficiency.

Thus, this study aims to clusterize a sample of houses according to their thermal performance and find the main architectural features that define each cluster.

## **Method**

### ***Data acquisition***

Data used in this work were obtained from an existing database of a previous research. In this research, low-income houses were audited in pre-selected areas where measurements and interviews by applying semi-structured questionnaires were performed. As selection criteria, these houses should have a family income equal to or less than three minimum monthly wages or be located in urban areas for low-income housing. Data regarding architectural features such as internal and external dimensions, spatial distribution of rooms and solar orientation of the front façade were obtained for each house. Information on size of doors and windows was also obtained. The fabric that composes the construction system was also recorded, and obtained from the knowledge of the occupant or through visual inspection of the interviewer. For the survey, measuring tape, compass and a semi-structured questionnaire, on which a sketch of the house was made, were used.

### ***Computer simulation***

Following the data acquisition step, virtual models based on the features of each house were developed, for the climate of Florianópolis (latitude 27° South, longitude 48° West). All models were simulated using the software EnergyPlus, version 8.5, in order to obtain the thermal performance of each long-term room. The files related to each model have been configured so that all parameters remain the same in all models, with the exception of those related to its geometry and fabric. Only natural ventilation was configured in the simulations, since no air-conditioner was found in the sample. The internal operating temperature value for each long-term room, for every hour of the year, was the output data used from the simulations. Based on the operative temperature, two variables representing the thermal performance of the house, the heating and cooling degree-hours, were calculated for each month of the year, as shown in Eqs. 1 and 2. To summarize the analysis, a weighting average of degree-hour according to the volume of each room was estimated, finding a comparable value of cooling and heating for the house as a whole. This step was necessary since the houses of the sample have different number of rooms, which makes it difficult to compare the houses.

$$GH_R = \sum(T_o - 26^\circ C) \quad (1)$$

$$GH_A = \sum(18^\circ C - T_o) \quad (2)$$

where  $GH_A$  is the heating degree-hour [ $^{\circ}\text{Ch}$ ];  $GH_R$  is the cooling degree-hour [ $^{\circ}\text{Ch}$ ];  $T_o$  is the operative temperature of each room in each hour of the year [ $^{\circ}\text{C}$ ].

### **Cluster analysis**

The application of the cluster analysis was conducted with Minitab 17, and the procedures, measures and algorithms were adopted as suggested by Schaefer and Ghisi (2016).

The variables from the previous step (degree-hours for heating and cooling for each month of the year in each house) were standardized, avoiding that the variables with greater dispersion of data exerted a greater impact on the results. For this, the statistical standardization (z-scores) was adopted in order to obtain for each variable a set of data whose average is equal to zero and standard deviation equal to one. Statistical standardization was performed using Eq. 3.

$$Z_{x_i} = \frac{(x_i - \bar{x})}{s} \quad (3)$$

where  $Z_{x_i}$  is the standardized value of  $x$ ,  $\bar{x}$  is the average of determined variable values,  $s$  is the standard deviation of the determined variable values.

From the standardized database, the distance between each pair of sample objects with the measure of similarity, the square Euclidean distance, was calculated using Eq. 4.

$$d_{AB} = \sum (x_{iA} - x_{iB})^2 \quad (4)$$

where  $d_{AB}$  is the square Euclidean distance from object A to object B,  $x_{iA}$  is the value of the object A for each variable,  $x_{iB}$  is the value of the object B for each variable.

Subsequently, there was the partitioning process, in which the objects were divided into groups based on the similarity or not of their characteristics (i.e., individuals with similar profiles are grouped into one cluster while different profiles form distinct clusters). The hierarchical partition technique was adopted, applying the Ward Method as partitioning algorithm. In the hierarchical technique, within each new step two objects are united, process that allows the construction of a graph called dendrogram. It is possible to make a visual analysis of a dendrogram regarding the ideal formation of clusters. The Ward algorithm separates the clusters based on the sum of the residual squares within each group.

Finally, each cluster found was described according to its architectural features. Thus, based on the differences between each group, it was possible to infer which characteristics would be associated with best or worst performance (i.e., what are the characteristics of the houses that make up the group with the worst performance? And the best?).

## **Results**

A sample composed of 102 low-income houses, described according to their geometric and material characteristics, was obtained for this study. These data were used to construct the virtual models, from which the degree-hour of cooling and heating for each month was obtained for each house.

With the application of the hierarchical technique (Ward algorithm) of clustering, the dendrogram was obtained, from which it was possible to determine the ideal number of clusters for that sample. Fig. 1 shows the dendrogram obtained and the clusters found. In the vertical axis the calculated distances for each join group are presented, while in the horizontal axis all the houses of the sample are presented. As it can be seen from Fig. 1, the stop rule was made with height 5 and the sample was then divided into three distinct clusters, which is the best solution found.

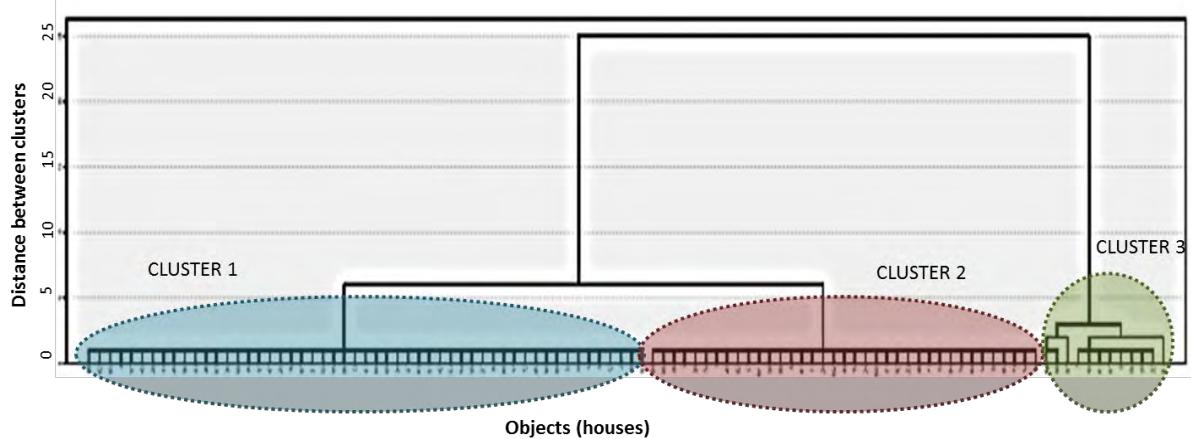


Fig. 1. Dendrogram obtained in the hierarchical partition step.

Fig. 2 shows a summary of the thermal performance found for each cluster. The degree-hour values are shown in the vertical axis, while the months of the year are shown in the horizontal axis. The average weighted cooling and heating degree-hour of houses of each cluster are presented for each month. It is possible to verify that the three clusters differ in their thermal performance. Cluster 1 showed the worst performance for both hot and cold seasons. Cluster 2, on the other hand, presented the best performance among the three clusters, with nearly no heating degree-hour in most months. Finally, Cluster 3 presented an intermediate performance, both for cooling and heating. For all clusters, a preponderance of cooling degree-hour was found, being more significant than heating degree-hour. The cooling degree-hour was found for every month and all clusters.

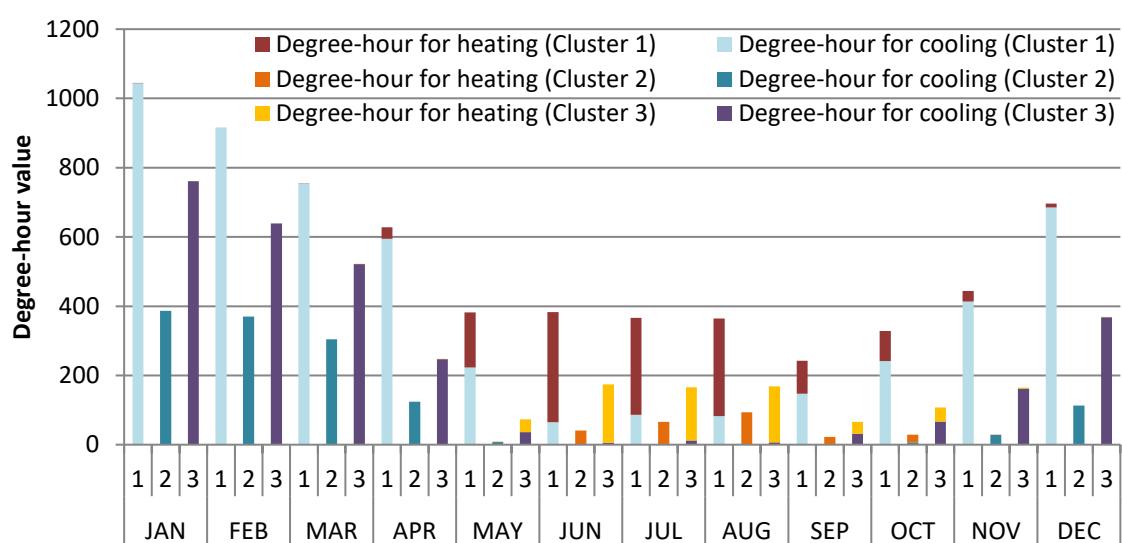


Fig. 2. Cooling and heating degree-hour of Clusters 1, 2 and 3 in each month of the year.

Fig. 3 and Table 1 show some data on the geometry of the houses under study. In Fig. 3 it is possible to observe that houses with combined kitchen and living room predominate in Clusters 1 and 3. The opposite occurs in Cluster 2 (group with better thermal performance), where houses in which these rooms configure independent spaces predominate. Most houses in Cluster 1 (73%) also have only two bedrooms, whereas in the other clusters houses with two or three bedrooms are more frequent. As far as solar orientation is concerned, Cluster 1, the group with the worst performance, is mainly composed of houses with solar orientation of the frontal façade facing north. In the other two clusters, this distribution is more balanced. Because of the way in which the internal distribution of the rooms in these houses is generally arranged, the orientation of the north-facing front façade may represent an important factor in the thermal performance. It is in this façade where the living room and the main bedroom are usually located and it is reached by solar radiation all-day-long.

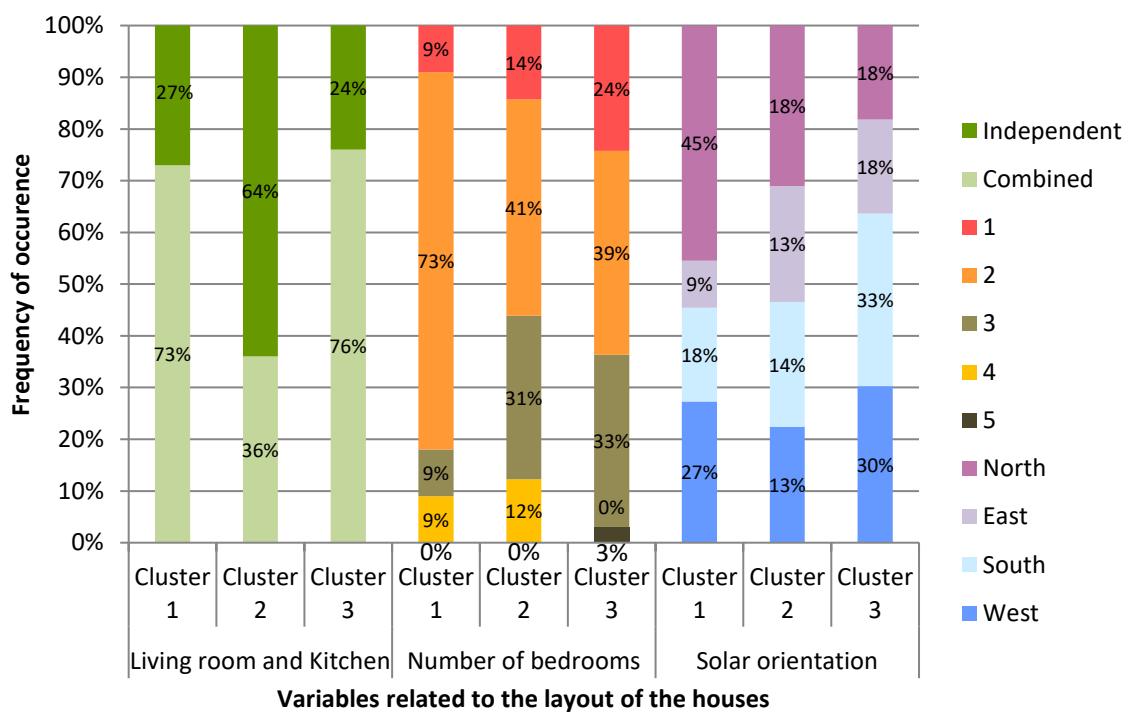


Fig. 3. Variables related to the layout of the houses of each cluster.

In Table 1 it is also possible to identify some characteristics that diverge between clusters and that may be impacting the performance of the houses negatively or positively. The ceiling height, for example, is higher in the cluster with the best performance (Cluster 2), and lower in the cluster with the worst performance (Cluster 1). The same happens with the floor plan areas and volumes of rooms: in the houses in Cluster 1, there is a trend of smaller houses, with smaller floor plan area and volume, taking account the whole house or even only the long-term rooms, while Cluster 2 is composed of larger houses and Cluster 3, of houses with intermediate dimensions. This may be related to the performance of the houses of each group because, having a greater volume, it is necessary to provide a greater amount of energy to change the temperature conditions of that environment. In this way, larger houses tend to keep their temperature more constant, being less subject to external environmental variations. Also, houses in Cluster 2 have a larger window area in long-term rooms, thus favouring cross ventilation.

Table 1. Variables related to the geometry of the houses of each cluster.

Variables	Cluster 1		Cluster 2		Cluster 3	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
North façade/East façade ratio	1.11	0.61	1.13	0.50	0.98	0.41
Building Ratio <sup>1</sup>	0.53	0.15	0.57	0.20	0.62	0.20
Ceiling height (m)	2.34	0.19	2.54	0.18	2.48	0.20
Total floor plan area (m <sup>2</sup> )	46.01	23.12	61.64	21.20	50.85	16.62
Total volume <sup>2</sup> (m <sup>3</sup> )	106.68	51.02	157.10	57.53	126.12	40.95
Long-term rooms floor plan area (m <sup>2</sup> )	36.37	19.33	42.76	14.94	38.89	12.03
Long-term rooms volume <sup>2</sup> (m <sup>3</sup> )	83.68	40.59	108.97	40.29	96.44	29.35
Private rooms volume <sup>3</sup> (m <sup>3</sup> )	45.48	27.55	63.44	24.07	48.04	20.69
Average volume <sup>2</sup> of bedrooms (m <sup>3</sup> )	20.83	4.32	27.03	6.06	22.72	4.92
Social rooms volume <sup>4</sup> (m <sup>3</sup> )	38.20	22.16	45.53	25.49	48.40	20.09
North façade area <sup>5</sup> (m <sup>2</sup> )	15.43	5.27	22.60	7.30	17.59	5.12
South façade area <sup>5</sup> (m <sup>2</sup> )	15.43	5.27	20.83	7.19	17.26	5.21
East façade area <sup>5</sup> (m <sup>2</sup> )	17.66	8.86	20.03	5.94	19.18	6.03
West façade area <sup>5</sup> (m <sup>2</sup> )	17.66	8.86	20.03	5.94	19.18	6.03
North window area <sup>6</sup> (m <sup>2</sup> )	1.38	0.98	1.79	1.48	1.08	1.19
South window area <sup>6</sup> (m <sup>2</sup> )	1.04	1.09	1.68	1.78	1.56	1.18
East window area <sup>6</sup> (m <sup>2</sup> )	0.90	0.84	1.41	1.14	1.44	1.08
West window area <sup>6</sup> (m <sup>2</sup> )	1.75	1.46	1.59	1.93	1.55	1.19

<sup>1</sup>Ratio smallest/ largest façade; <sup>2</sup> Floor plan area x ceiling height; <sup>3</sup>Sum of bedroom's volumes; <sup>4</sup>Living room or combined kitchen and living room's volumes; <sup>5</sup>Sum of areas of all long-term rooms external walls; <sup>6</sup>Sum of areas of all long-term rooms windows.

Figs. 4–6 show the materials that the houses in Clusters 1, 2 and 3 are made of. Fig. 4 shows the frequency distribution of cases for each type of wall material. Cluster 1, which obtained the worst thermal performance (Fig. 2), is composed of houses made of wooden walls, while Cluster 2, with the best performance, is composed of houses made of masonry walls of ceramic blocks. Cluster 3, which obtained a medium performance, has a mixed sample, consisting of houses with walls of wood and ceramic blocks, and also houses with walls of concrete blocks. The material of the walls proved to be a very important factor in the thermal performance of the houses.

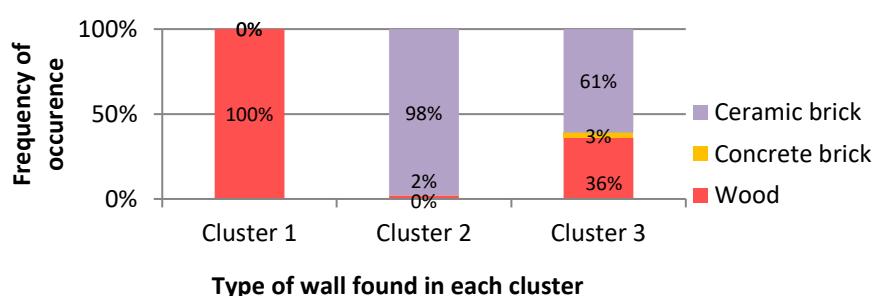


Fig. 4. Frequency distribution of wall material for each cluster.

Fig. 5 shows the frequency distribution of cases for the material type used on the floor, as well as the contact with the ground or not. As for the walls, a great difference in the composition of the floor of Clusters 1 (wood) and 2 (concrete) was observed, while Cluster 3 shows a more heterogeneous distribution. The same is true for ground contact: this is more representative (97% of cases) for Cluster 2, while in the other two clusters there are predominant cases in which the houses do not have the floor slab in contact with the ground.

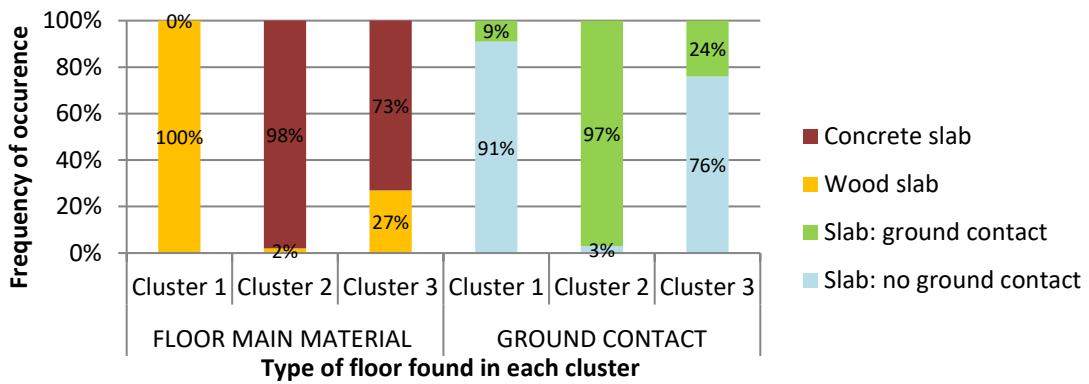


Fig. 5. Frequency distribution of floor material for each cluster.

Fig. 6 shows the roof composition for each of the clusters. Cluster 1 consists mainly of houses with a roof made of ceramic tiles and wood lining, without the existence of a concrete slab between the tile and the lining. However, Clusters 2 and 3 show a balance between the use of ceramic tiles and concrete tiles, and also a predominant use of wood lining. Because of the similar compositions, it was not possible to identify the roofing materials as influential factors in the performance of the sample, except for the existence of concrete slab, which did not exist in houses in Cluster 1 (which had the worst performance).

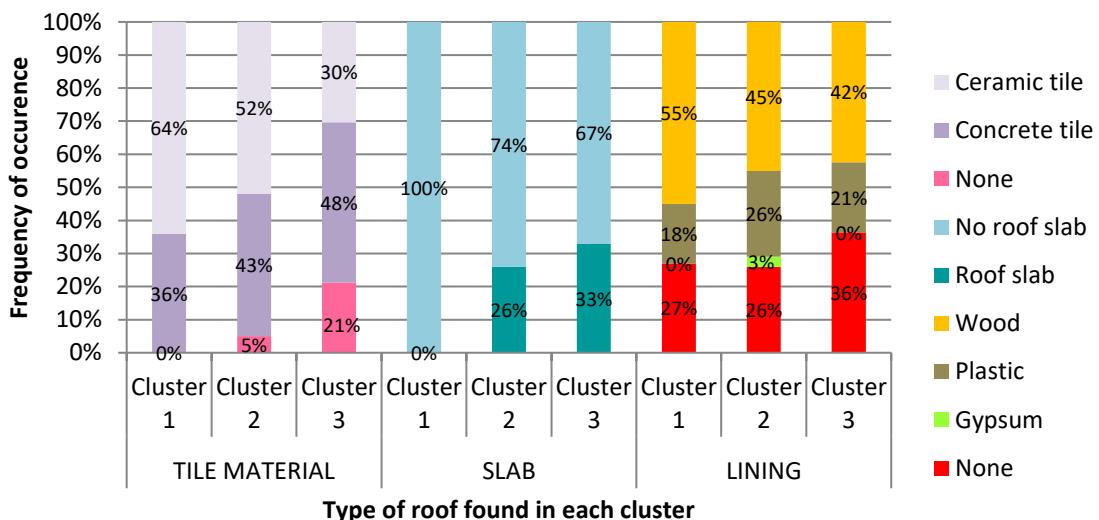


Fig. 6. Frequency distribution of roof material for each cluster.

## Conclusion

In this study, 102 low-income houses virtual models were subjected to computer simulation in order to obtain their thermal performance, described in this study through the heating and cooling degree-hour indicators. A cluster analysis was performed and three clusters with different thermal performance profiles were found.

Cluster 1, the group with the worst performance, has reached 6548 degree-hours per year (5249 for cooling and 1298 for heating). Cluster 2, the group with the best performance, has reached 1589 degree-hours per year (1345 for cooling and 243 for heating). Cluster 3, the

intermediate performance group, has reached 3458 degree-hours per year (2859 for cooling and 599 for heating).

The main architectural features difference of clusters seems to rely on its size and fabric. Cluster 1 is composed of a sample of houses with wooden walls and floor, and no slab on the roof, while Cluster 2 is mainly composed of houses with walls made of ceramic block, concrete slab on the floor and concrete slab in the roof of some houses. Because of the difference on the transmittance of these materials, the houses in Cluster 1 are more susceptible to changes in the outside environment, which causes their bad performance. Also, the size of the houses appears to have some influence on their performance too, since Cluster 1 is composed of smaller houses, while Cluster 2 is composed of larger houses. This can influence their performance since having a larger space to heat or to cool, a larger amount of energy is necessary, so the internal temperatures increase or decrease in a slower process.

Finally, it was possible to conclude that the architectural features of those houses can significantly influence their performance. The promotion of design and material guidelines and public policies regarding energy efficiency measures can contribute to improve the performance of future houses.

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## References

- Bodach, S. and Hamhaber, J. (2010). Energy efficiency in social housing: Opportunities and barriers from a case study in Brazil. *Energy Policy*, 38(12): 7898–7910.
- Dascalaki, E. G., Droutsas, K. G., Balaras, C. A. and Kontoyiannidis, S. (2011). Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock. *Energy and Buildings*, 43(12): 3400–3409.
- Fracastoro, G. V. and Serraino, M. (2011). A methodology for assessing the energy performance of large scale building stocks and possible applications. *Energy and Buildings*, 43(4): 844–852.
- Hair, J. F.; Anderson, R. E.; Tatham, R. L.; Black, W.C. (2009). *Análise Multivariada dos Dados*. Porto Alegre: Bookman.
- IEA. (2012). *Key World Energy Statistics*. Paris.
- McNeil, M. A. and Letschert, V. E. (2010). Modeling diffusion of electrical appliances in the residential sector. *Energy and Buildings*, 42(6): 783–790.
- MME. (2015). *Balanço Energético Nacional: Relatório Final*. Brasília: Ministério de Minas e Energia.
- Schaefer, A.; Ghisi, E. (2016). Method for obtaining reference buildings. *Energy and Buildings*, v. 128, p. 660-672.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Thermal Preference, Comfort and Satisfaction: Norwegian and British workplaces

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**Abstract:** Many researchers in thermal comfort area mainly focus on user's thermal sensation ignoring the importance of thermal preference. This study investigates the impact of thermal preference of the user on their perception of user's comfort and satisfaction. Field studies of thermal comfort were applied in two contexts of Norwegian personal offices and British open plan offices. Environmental measurements, survey questionnaires and follow up interviews were applied. Qualitative and quantitative methods of analysis were applied. The results indicated that overall, users' desire to adjust the thermal environment, including temperature, air quality and air movement, highly impacted their satisfaction and comfort level. Comfortable and satisfied users had no or low preference to adjust the thermal environment (temperature, air quality and air movement), while uncomfortable and dissatisfied occupants had a great preference to control the thermal environment. 89% of the satisfied and 77% of the comfortable respondents wanted either no change or a slight thermal adjustment. 100% of the dissatisfied and 100% of the comfortable participants wanted to change the temperature or ventilation. 85% of the dissatisfied and 73% of the uncomfortable respondents wanted more than a slight change. The study emphasises the importance of thermal preference in thermal comfort research.

**Keywords:** Thermal preference, Comfort, Satisfaction, Field Studies of Thermal Comfort, Workplace

### Introduction

The nature of comfort is complicated and it cannot be 'implied by simple prescriptions' (Hawkes, 2002). Thermal comfort research is focused on thermal sensation and the 'neutral thermal sensation' in particular (Zhang et al, 2011, Kwong et al, 2014). The latter is the measure of thermal comfort (Voelcker, 2002) and the most widely used survey questionnaire is on this basis: ASHRAE seven point thermal sensation scale (ASHRAE, 2004, Shahzad, 2014). Hawkes describes the definition of thermal comfort according to thermal neutrality, as an 'intermediate point, when neither cold nor hot' (Hawkes, 2002). Brengelmann et al (1997) describe the 'neutral zone' as 'the range in which thermal balance can be achieved without resorting to sweating or shivering', which is closely related to Olgay's (1992) definition of thermal comfort. Although ASHRAE (2009) also introduces thermal preference, comfort and satisfaction scales (shown in Table 1), the ASHRAE thermal sensation scale remains as the most widely used measure of thermal comfort. Recently

some researchers use thermal preference (shown in Table 1) in assessing thermal comfort. Advanced research in thermal comfort is shifting away from the ‘neutral thermal sensation’ (Rijal et al., 2009, Lee et al., 2009, Arens et al., 2010, de Dear, 2011, Humphreys et al., 2011, Bos et al, 2013). However, the application of thermal preference remains limited and main stream of thermal comfort research is still focused on thermal neutrality (Liu et al., 2012, Cigler et al., 2012, Indraganti et al., 2013). This study investigated the accuracy of thermal sensation scale and the application of thermal preference in assessing thermal comfort in the context of British and Norwegian workplaces.

Table 1: The ASHRAE scales (ASHRAE, 2009)

Thermal sensation scale:						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3
Thermal preference scale:						
Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
-3	-2	-1	0	1	2	3
Comfort scale:						
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
-3	-2	-1	0	1	2	3
Satisfaction scale:						
Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

## Thermal Neutrality and Thermal Preference

In some literature, ‘thermal neutrality’ is used instead of thermal comfort. For instance, the ASHRAE Handbook (2009) states that ‘acceptability is determined by the percentage of occupants who have responded neutral or satisfied (0, +1, +2, or +3) with their thermal environment’. Fanger (1970) expresses the importance of the neutral thermal sensation that ‘it is especially the relationship around the neutral point which is of interest. ... Thermal neutrality for a person is defined as the condition in which the subject would prefer neither warmer nor cooler surroundings. Thus thermal neutrality is a necessary condition for thermal comfort, but it need not be a sufficient condition’ (Fanger, 1970). McCartney and Nicol (2002) define the comfort temperature as ‘the indoor operative temperature at which an average subject will vote comfortable (or neutral) on the ASHRAE scale’. The PMV model ‘prescribes a certain range around the neutral temperature as acceptable, depending on the permitted percent dissatisfied’ (Fanger, 2002).

Despite all this emphasis on thermal neutrality, its application has been questioned by researchers (Humphreys et al, 2007, Shahzad et al, 2017). ‘Do people want to feel neutral?’ (Humphreys et al, 2007). De Dear also explains that using the ‘neutral thermal sensation’ on the PMV seven point scale ‘says nothing about whether the occupants are actually going to like it’ (de Dear, 2011). In a study, Humphreys reveals that ‘the data contain 868 comparisons of the actual and the desired sensation. On 57% of occasions the desired

sensation was other than “neutral”. He reports that ‘there were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others’. He concludes that ‘if there is sufficient adaptive opportunity, people who feel ‘slightly warm’ perhaps desire at that time to feel ‘slightly warm’, while people who feel ‘slightly cool’ perhaps desire to feel ‘slightly cool’, and so on’. Recently some papers consider users’ preference to feeling comfortable when experiencing other sensations than ‘neutral’ and they apply different methods for this investigation. However, still many studies use thermal neutrality to investigate aspects of thermal comfort.

Some new scales are introduced to cover the difficulties of the ASHRAE seven point scale, such as ‘much too cool, too cool, comfortably cool, neutral, comfortably warm, too warm and much too warm’ (Nicol et al, 2009). Humphreys explains ‘the need to ascertain more precisely the desired thermal sensation on the scale led researchers to supplement it with a scale of thermal preference, which asked people whether they would prefer to feel warmer or cooler, or whether they desired no change’ (Humphreys, 2009). They explain ‘the need to ascertain more precisely the desired thermal sensation on the scale led researchers to supplement it with a scale of thermal preference, which asked people whether they would prefer to feel warmer or cooler, or whether they desired no change’. It is recommended to use both thermal sensation and thermal preference (Oseland et al, 1994, Nicol et al, 2012). Researchers introduced different scales for thermal preference, such the ASHRAE nine-point thermal sensation scale, the EN-ISO 4-point thermal comfort scale, Bedford scale (1936) for thermal comfort, Fox scale for thermal preference (1973), the six-point comfort scale (Arens et al, 2006), and the three-point comfort scale (Lai, 2014). Some scales are a combination of thermal sensation and thermal preference, but they are reported as confusing and therefore the use of separate scales is recommended (Oseland et al, 1994). Currently some field studies of thermal comfort use a combination of the ASHRAE seven-point thermal sensation scale and the three-point McIntyre (1976) scale (cooler, no change and warmer). The three point McIntyre scale simply measures whether the occupant wants a change in temperature or not and it does not reveal the degree of thermal change, which is desired (Humphreys et al, 2007). They use the ASHRAE scale as a double enquiry method, as presented in Table 2.

Table 2: The ASHRAE scale for double enquiry method used by Humphreys et al (2007)

How do you feel just now? Based on the [6]						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
1	2	3	4	5	6	7
How would you like to feel just now? [29]						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

This is similar to the combination of the ASHRAE seven-point scale of thermal preference combined with the seven-point thermal sensation scale (see Table 1), which has been recommended (Humphreys et al, 2007, Fountain et al, 1996), and adopted in several studies (Johansson et al, 2014, Nematchoua et al, 2014). Sherman (1985) points out the difference between thermal sensation and preference, as he explains that the PMV model ‘is a measure of the thermal sensation (not preference)’. ‘Thermal neutrality is not

necessarily ideal for a significant number of people and preferences for non-neutral thermal sensations are common, very asymmetrically around neutrality, and in several cases are influenced by season. Also, thermal sensations outside of the three central categories of the ASHRAE seven-point scale of thermal sensation do not necessarily reflect discomfort for a substantial number of persons' (Van Hoof, 2008). The works of Humphreys, Nicol and de Dear shed light upon research in thermal comfort leading it away from simply considering the 'neutral thermal sensation', as other thermal sensations, which may be acceptable for the user, are considered important as well. Despite all this effort, still the focus of thermal comfort literature and research is thermal neutrality, such as in (Cheong et al, 2007, Leyten et al, 2013, Liu et al, 2013, Cigler et al, 2012, Indraganti et al, 2013).

## **Methodologies**

This study investigates the application of thermal preference combined with thermal sensation in assessing thermal comfort of occupants and it questions the accuracy of thermal neutrality as the sole measure of thermal comfort. Field studies of thermal comfort were applied in four workplaces in the UK and Norway in the summer of 2012. Occupants views of thermal environment were recorded using a survey questionnaire, mainly the ASHRAE seven point scale for thermal sensation, thermal preference, comfort and satisfaction, as presented in Table 1. Environmental measurements of the air temperature, relative humidity and mean radiant temperature were recorded at the time of the survey. This was followed up by interviews to investigate users' thermal preferences further. Quantitative regression analysis was applied using the statistical analysis software (SPSS) on the PMV and survey variables, including comfort, satisfaction, thermal sensation, and preference. The probability of gaining results equal or beyond observation (P value) was examined. Sedentary activities took place in the case study buildings. Overall, 313 responses were included in this study with a good range of age and gender and between 68 to 95 responses from each building.

## **Analysis**

In order to limit the impact of the thermal environment on occupants' views, good practice examples of workplaces were selected for this study. The thermal conditions of the workplaces were analysed using the PMV model. Air temperature, relative humidity and mean radiant temperature were measured and clothing and activity were observed. The PMV model was calculated using the ASHRAE Thermal Comfort Tool (Huizenga, 2010) and compared against the ASHRAE Standard 55-2013. Overall, 91% of the workstations in the four case study buildings were expected to provide comfortable thermal conditions for the occupants. Therefore, the thermal perception of the respondents is less likely to be related to the poor quality of thermal conditions of the workplace, as they were within a good range of mainly neutral or slightly cool thermal sensation. The relationship between thermal sensation, thermal preference, comfort, and satisfaction were examined against the PMV through regression analysis. The analysis indicated no significant relationships between the PMV predictions and the variables: thermal sensation ( $P$  value =  $0.084 > 0.05$ ), thermal preference ( $P$  value =  $0.185 > 0.05$ ), comfort ( $P$  value =  $0.569 > 0.05$ ), and satisfaction ( $P$  value =  $0.694 > 0.05$ ). Although the PMV model predicted relatively good and similar thermal environments in all four buildings, this was not related to respondents' report of their thermal sensation, thermal preference, comfort, and satisfaction statuses. This

suggested that the quality of the thermal environment had limited effect on the comfort status of the occupants.

The SPSS linear regression analysis was applied on the relationship between thermal sensation and comfort. It showed that thermal sensation of respondents explained 13.2% of the variance in their comfort level. Every degree increase on the four-point thermal sensation scale towards ‘neutral’ improved comfort level of the user up to 0.565 on the ASHRAE seven-point scale towards ‘very comfortable’. Overall, the analysis indicated a significant relationship between comfort and thermal sensation ( $P$  value = 0.000 < 0.05). Figure 1 demonstrates the relationship between comfort and thermal sensation according to the survey responses. Participants, who felt comfortable, had a relatively small range of thermal sensation between ‘neutral’ and ‘slightly warm’. In contrast, participants who felt uncomfortable had a much wider range of thermal sensations between ‘cool’ to ‘hot’. Respondents, who felt the extremes of the thermal sensation, were more likely to be uncomfortable. It also showed comfort when respondents felt ‘slightly warm’, while discomfort when they felt ‘neutral’. The thermal sensation of the comfortable respondents (comfortable and very comfortable responses only) was mainly between ‘slightly cool’ to ‘slightly warm’ with the majority falling into the ‘neutral’ category. Respondents who felt the extreme thermal sensations were mostly uncomfortable. Over 30% of the respondents with a neutral thermal sensation reported as “not comfortable”.

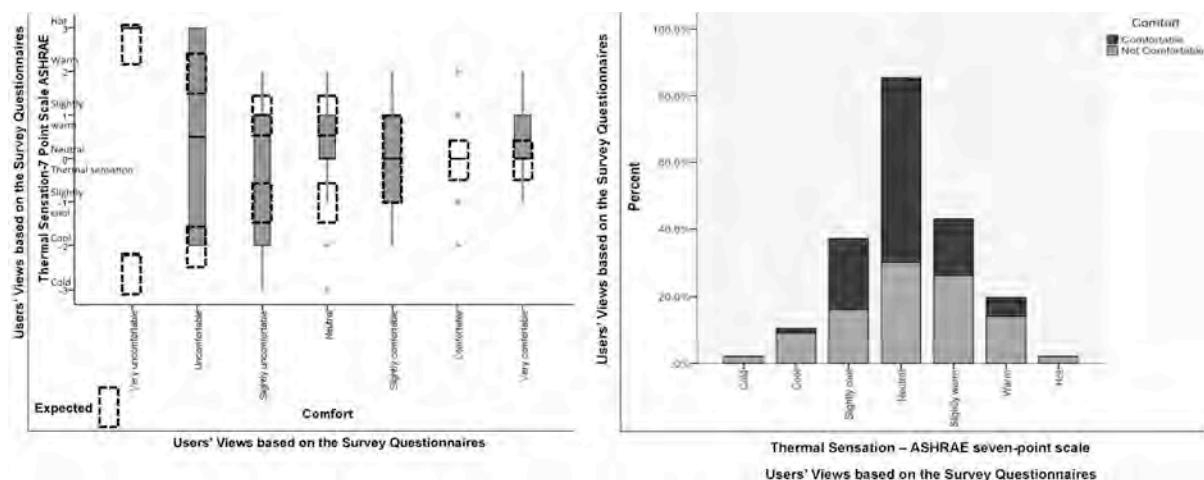


Figure 1. Analysis of comfort and thermal sensation based on the ASHRAE seven-point scale survey responses

The statistics showed a strong relationship between thermal sensation and satisfaction ( $P$  value = 0.000 < 0.05). Figure 2 Shows that ‘very satisfied’ participants felt between ‘slightly cool’ to ‘slightly warm’, while ‘very dissatisfied’ users had a much wider range of thermal sensation from ‘slightly cool’ to ‘hot’. Respondents, who felt the extremes of thermal sensation, were more likely to be dissatisfied. However, some respondents with ‘warm’ or ‘cool’ thermal sensations report feeling ‘comfortable’, while some ‘dissatisfied’ participants report feeling ‘neutral’ regarding the thermal environment.

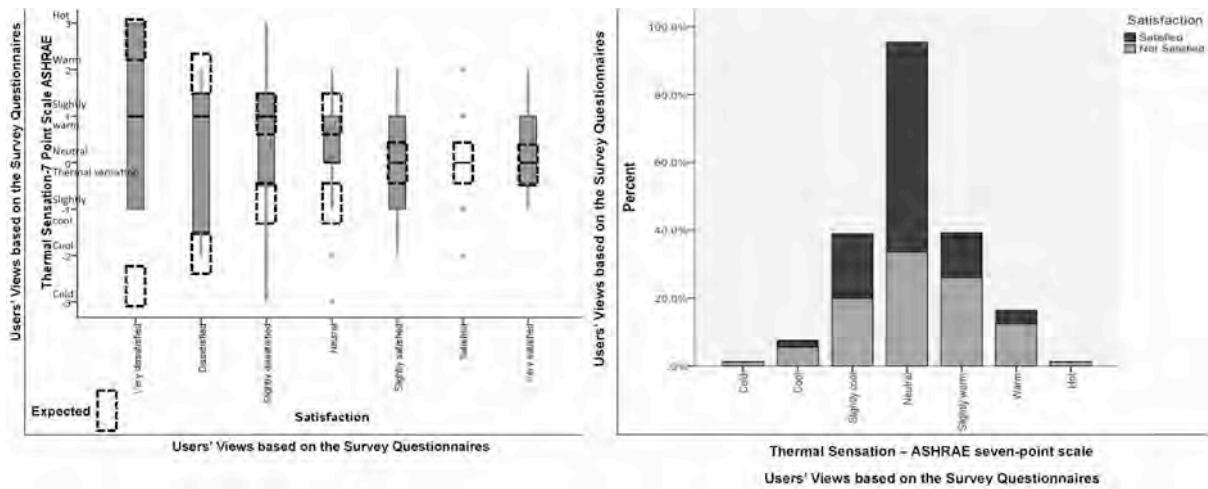


Figure 2. Analysis of satisfaction and thermal sensation based on the ASHRAE seven-point scale survey responses

The regression analysis indicated a significant relationship between thermal sensation and preference (i.e. P value = 0.000 < 0.05). Figure 3 shows that except for the cases of 'cold' and 'hot' thermal sensations, there is a consistency between thermal sensation and thermal preference of the user with a tendency to restore a 'neutral' sensation. For instance, respondents with a 'neutral' thermal sensation want 'no change' in the thermal environment and the majority of the respondents with a 'slightly warm' thermal sensation prefer a 'slightly cooler' thermal setting. Majority of the respondents, who felt neutral, preferred no change in the temperature. Respondents with extreme thermal sensations were more likely to prefer a change in the temperature. When thermal sensation and thermal preference were combined (thermal decision), 36% of the respondents did not want to feel neutral. 25 occupants (i.e. 8%) felt neutral but preferred to feel thermal sensations other than neutral. 77 respondents (i.e. 25%) already felt neutral but the thermal changes they wanted would not add up to a thermoneutral sensation. 13 respondents (i.e. 3%) wanted to feel beyond the range of slightly cool, neutral and cool, as they preferred to feel warm, hot, cool or cold. In the follow up interviews, 70% of the participants acknowledged individual differences in perceiving the thermal environment. When asked what thermal sensation they would prefer to feel when working, 40% of them wanted 'slightly cool' and 'cool' to feel fresh and not sleepy, and 30% preferred feeling 'slightly warm' to 'warm', due to the lack of movement and the sedentary nature of the work. Only 30% of them wanted a 'neutral thermal sensation' when working. Most members of this group considered thermoneutrality the 'obvious' choice.

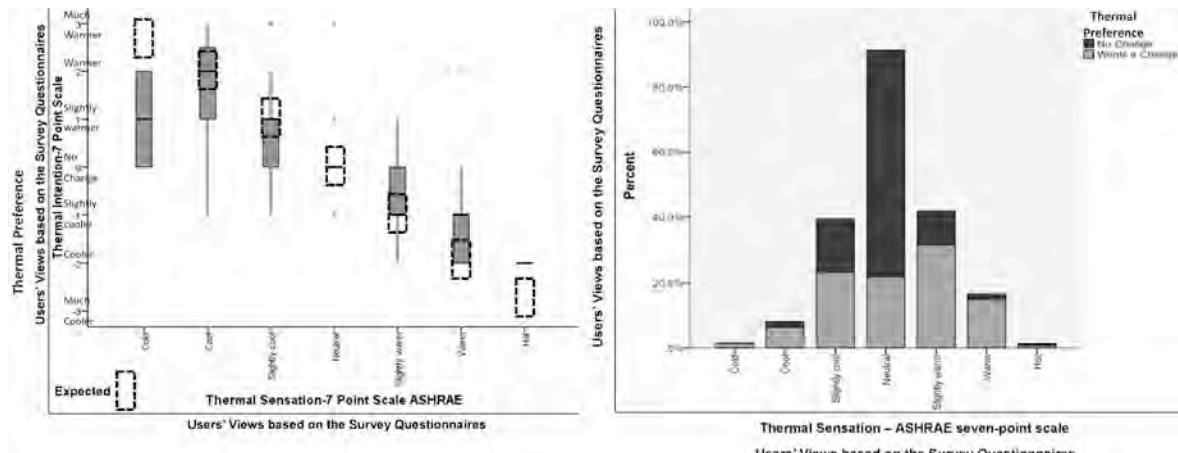


Figure 3. Analysis of thermal preference (intention) and thermal sensation based on the ASHRAE seven-point scale survey responses

## Discussion and Conclusion

The results indicate that thermal neutrality does not guarantee thermal comfort, as respondents may prefer other sensations than neutral to feel comfortable. 36% of the occupants preferred not to feel neutral. This is in agreement with the findings of Humphreys et al (2007). Over 30% of the responses were not consistent between comfort, satisfaction and thermal sensation. The follow up interviews revealed that 60% of the respondents did not want to feel neutral when working. These findings did not agree with some assumptions and misjudgements in the field of thermal comfort. For example, the findings did not agree with Hawkes' (2002) definition of thermal comfort as the 'intermediate point, when neither cold nor hot'. Most studies ignore the importance of whether or not the respondent prefers a change in the temperature and simply rely on the thermal sensation of the respondent. This study recommends the application of the dual enquiry method of the thermal sensation and thermal preference. Since the ASHRAE seven point scale of thermal sensation is widely used in thermal comfort research, it is suggested to use the ASHRAE seven point thermal preference scale to be used, as it shows the degree of desired change and can be comparable with the relevant thermal sensation scale. Furthermore, by questioning thermal neutrality, this study questions the findings of the studies that solely rely on thermal sensation scale and neutral thermal sensation to assess thermal comfort.

## References

- Hawkes, D. (2002). *The Selective Environment; An approach to environmentally responsive architecture*, London, Spon Press.
- Zhang H, Arens E, Pasut W. (2011). Air temperature thresholds for indoor comfort and perceived air quality. *Building Research & Information*. Apr 1;39 (2):134-44.
- Kwong QJ, Adam NM, Sahari BB. (2014). Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. *Energy and Buildings*. Jan 31;68:547-57.
- Standard, ASHRAE. (2004). Standard 55-2004. *Thermal Environmental Conditions for Human Occupancy*. ASHRAE Inc., Atlanta, GA.
- Shahzad SS. (2014). Individual thermal control in the workplace: cellular vs open plan offices: Norwegian and British case studies.
- Brengelmann, G.L. and Savage, M.V., (1997). Temperature regulation in the neutral zone. *Annals of the New York Academy of Sciences*, 813(1), pp.39-50.
- Olgay, V. 1992. *Design with Climate: bioclimatic approach to architectural regionalism*, New York.
- Handbook AS. (2009). *ASHRAE handbook—fundamentals*. Atlanta, GA.

- Rijal HB, Humphreys MA, Nicol JF. (2009). Understanding occupant behaviour: the use of controls in mixed-mode office buildings. *Building Research & Information*. Aug 1;37(4):381-96.
- Lee JY, Tochihara Y, Wakabayashi H, Stone EA. (2009). Warm or slightly hot? Differences in linguistic dimensions describing perceived thermal sensation. *Journal of physiological anthropology*. 28(1):37-41.
- Arens E, Humphreys MA, de Dear R, Zhang H. (2010). Are 'class A' temperature requirements realistic or desirable? *Building and Environment*. Jan 31;45(1):4-10.
- De Dear R. (2011). Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*. Apr 1;39(2):108-17.
- Humphreys MA, Rijal HB, Nicol JF. (2010). Examining and developing the adaptive relation between climate and thermal comfort indoors. In proceedings of conference: Adapting to change: new thinking on comfort, Windsor, UK, Network for Comfort and Energy Use in Buildings, London. Apr 9 (pp. 9-11).
- Bos MA, Love JA. (2013). A field study of thermal comfort with underfloor air distribution. *Building and Environment*. 2013 Nov 30;69:233-40.
- Liu J, Yao R, Wang J, Li B. (2012). Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems. *Applied Thermal Engineering*. 2012 Mar 31;35:40-54.
- Cigler J, Prívara S, Váňa Z, Žáčeková E, Ferkl L. (2012). Optimization of predicted mean vote index within model predictive control framework. *Energy and Buildings*. Sep 30;52:39-49.
- Indraganti M, Ooka R, Rijal HB. (2013). Thermal comfort in offices in summer: findings from a field study under the 'setsuden' conditions in Tokyo, Japan. *Building and Environment*. Mar 31;61:114-32.
- Fanger PO. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering*.
- Fanger, P.O. and Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and buildings*, 34(6), pp.533-536.
- Humphreys MA, Hancock M. (2007). Do people like to feel 'neutral'? Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and Buildings*. Jul 31;39(7):867-74.
- Shahzad, S., Brennan, J., Theodosopoulos, D. Hughes, B., Calautit, J. (2017) Neutral Thermal Sensation: Is it the Correct Response to Assess Thermal Comfort? CIBSE ASHRAE Symposium
- De Dear R. (2011). Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*. Apr 1;39(2):108-17.
- Oseland NA, Humphreys MA. (1994). Trends in thermal comfort research. BRI
- Nicol F, Humphreys M, Roaf S. (2012). Adaptive thermal comfort: principles and practice. Routledge.
- Bedford T. (1936). The Warmth Factor in Comfort at Work. A Physiological Study of Heating and Ventilation. Industrial Health Research Board Report. Medical Research Council. (76).
- Fox RH, Woodward PM, Exton-Smith AN, Green MF, Donnison DV, Wicks MH. (1973). Body temperatures in the elderly. *Br Med J*. Jan 27;1(5847):200-6.
- Arens E, Zhang H, Huizenga C. (2006). Partial-and whole-body thermal sensation and comfort—Part I: Uniform environmental conditions. *Journal of thermal Biology*. Jan 31;31(1):53-9.
- Lai D, Guo D, Hou Y, Lin C, Chen Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment*. Jul 31;77:110-8.
- McIntyre DA, Gonzalez RR. (1976). Man's thermal sensitivity during temperature changes at two levels of clothing insulation and activity. *ASHRAE Trans*. 82(2):219-33.
- Fountain M, Brager G, de Dear R. (1996). Expectations of indoor climate control. *Energy and Buildings*. Oct 1;24(3):179-82.
- Johansson E, Thorsson S, Emmanuel R, Krüger E. (2014). Instruments and methods in outdoor thermal comfort studies—The need for standardization. *Urban Climate*. Dec 31;10:346-66.
- Nematchoua MK, Tchinda R, Ricciardi P, Djongyang N. (2014). A field study on thermal comfort in naturally-ventilated buildings. *Renewable and Sustainable Energy Reviews*. Nov 30;39:381-93.
- Sherman M. A (1985). simplified model of thermal comfort. *Energy and buildings*. Feb 1;8(1):37-50.
- Cheong KW, Yu WJ, Sekhar SC, Tham KW, Kosonen R. (2007). Local thermal sensation and comfort study in a field environment chamber. *Building and Environment*. Feb 28;42(2):525-33.
- Leyten JL, Kurvers SR, Raue AK. (2013). Temperature, thermal sensation and workers' performance in air-conditioned and free-running environments. *Architectural Science Review*. Feb 1;56(1):14-21.
- Van Hoof J. (2008). Forty years of Fanger's model of thermal comfort. *Indoor air*. 1;18(3)
- Huizenga C. (2010) ASHRAE Thermal Comfort Tool CD, Version 2. ANSI/ASHRAE Standard 55-2010.
- Standard, ASHRAE. (2013). Standard 55-2013. Thermal environmental conditions for human occupancy.



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## An Investigation into Energy Consumption Behaviour and Lifestyles in UK Homes: Developing A Smart Application as A Tool for Reducing Home Energy Use

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**Abstract:** Research asserts that several domestic retrofit programmes in the UK have not achieved the expected levels of energy saving. Energy consumption is not only reliant on physical characteristics of buildings, but also on socio-economic and cultural factors. One of the issues is that the predicted home energy use may not reflect the actual energy consumed – a phenomena acknowledged as the ‘Building Performance Gap’. This study examines the factors that impact on domestic energy performance in response to this phenomenon. It adopts a concurrent mixed-method research design where the research method is primarily questionnaires to understand occupants’ energy consumption behaviour and lifestyle and develop a viable methodology to improve this. The solution could be the development of a smart application connected to smart meters that addresses energy consumption habits and behaviour. As a result, occupants will be advised in ‘real-time’ with appropriate energy-related behaviour once inefficient energy consumption actions is detected. Besides, the application will also comprise of a simplified Building Energy Simulation (BES) interface to provide building energy simulation results and evaluation. It is believed that this tool could potentially increase occupants’ awareness of energy consumption behaviour, reduce domestic energy consumption and ultimately reduce the Building Performance Gap (BPG).

**Keywords:** Smart Application, Building Energy Simulation (BES), energy efficiency application, domestic building stock, occupants’ behaviour

### Introduction

The average growth of energy demand in the UK was 7.3 percent between 1990 and 2003 (Environmental Change Institute, 2005). It has also been asserted that the growth of energy demand in the UK housing sector alone is 17.5 percent in the same period. Due to the rapid growth of residential housing developments; the housing energy demand increased by 32 percent by 2008 (Climate Change Act, 2008). Space heating has been noted as the main energy consumption source which contributes with 60 percent of all housing energy demand (Climate Change Act, 2008). However, the energy efficiency of the UK existing domestic stock has not improved much since 1970s.

This study focuses on possible routes for energy reduction in existing domestic buildings in the UK. Although the UK government has been proactively developing policies and programmes aiming to improve the uptake and delivery of retrofit schemes for domestic buildings since the 1970s, householders have not always been supportive to effective delivery, partially, due to lack of knowledge, awareness, financial and technical support (Long et al, 2014). The paper investigates the current conditions and issues of the low-carbon retrofit market in regards to occupants’ energy consumption behaviour and home energy

performance following the retrofit process. A number of significant factors concerning Building Energy Simulation (BES) and Energy Efficiency tools are also discussed such as the inaccurate results of building energy simulation, and the influences of smart metering devices on people's behaviour. One major issue highlighted is occupants' behaviour and its impact on building energy performance. The findings will contribute to the development of a smart application connected to smart meters that aims to address most energy consumption habits and behaviour.

### **Research Context - Low-carbon retrofit and occupants' behaviour**

Besides the establishment of the Climate Change Act (2008) which set out the target of 80 percent CO<sub>2</sub> reductions by 2050, the UK government aims to accelerate the process of domestic energy conservation. For example, some energy efficiency standards (DCLG, 2013a) were tightened in order to meet the targets. There has also been a large variety of retrofit strategies and technologies that have been developed. A number of programmes have been launched to support the successful delivery of low-carbon retrofit projects, such as the Decent Homes, the Warm Front, the Green Deal, the Carbon Emissions Reduction Target (CERT), the Community Energy Saving Programme (CESP), and the Landlord Energy Saving Allowance (LESA) (Dowson et al, 2012). Although the majority of the schemes have already been completed, whilst a few scrapped, the current major policies, such as the Feed-in Tariff (Fit) and the Renewable Heat Incentive (RHI), are still playing important roles in the retrofit projects (Dowson et al, 2012).

To evaluate the feasibility of the abovementioned programmes, several issues have been assessed. One of the issues is to identify proper project scale and approach. It is suggested that the wider the project spread, the more efficient the project will be (Webber et al., 2015; Smith and Swan, 2012). Besides, it is crucial to apply the most appropriate approaches; the housing physical conditions and socio-economic issues (Ma et al, 2012). In addition, the energy upgrade works have to be delivered in high standards as it will directly impact on the success or failure of the project (Gilbertson et al., 2008 and Long et al., 2014). This issue has also been reflected in several project reports (LDA, London Councils et al., 2010, 2011 and 2014; TSB, 2012 and 2014) which are developed by London Development Agency (LDA) and Technology Strategy Board (TSB). Nevertheless, the retrofit projects still might not meet the expectations even if they are fully delivered, partially due to occupants' energy consumption which would then impact on the energy performance of their homes.

The energy performance of buildings is subject to a wider range of variables, such as technical, social and behavioural factors which are not thoroughly considered by the construction industry stakeholders from designers to policy makers. These factors are called the 'hard-to-quantify' factors. The patterns that occupants operate their homes significantly affects actual building energy performance compared to predicted energy performance (Greening et al., 2000; Khazzoom, 1980; Saunders, 1992). This phenomenon is called Building Performance Gap (Sunikka-Blank and Galvin, 2016). It is, therefore, crucial to consider these 'hard-to-quantify' factors in the earlier project stages (Sorrell and Dimitropoulos, 2008; Hadjri and Crozier, 2009; Preiser et al., 1988; Zimring and Reizenstein, 1980; Chiu et al., 2004).

Among issues identified above, the research focuses on investigating the correlations between occupants' behaviour and home energy performance. Several propositions have been raised such as providing instruction manuals and offering tailored training to occupants (LDA, London Councils et al., 2010, 2011 and 2014; TSB, 2012 and 2014). As supplementary of the existing approaches, more efforts can be made on changing occupants' behaviour

through the development of a smart application connected with smart meters. The methodological approach adopted to achieve this is explained in the section below.

## **Research Methodology**

The research question is: How do occupants' behaviour, lifestyle patterns and socio-economic factors impact on the actual energy performance following energy-efficient retrofit delivery? The research is based on the assumption that a number of 'hard-to-quantify' factors, such as occupants' energy-related behaviour and attitudes towards energy consumption, have not been thoroughly taken into consideration in building energy simulation tools leading to the building performance gap (BPG).

This research examines the factors that impact on domestic energy performance in response to BPG. It adopts a concurrent mixed-method research design where the research method is primarily survey questionnaires to understand and analyse occupants' energy consumption behaviour and lifestyle to help develop a viable tool to improve this. The target group is occupants of two case studies in London Borough of Newham due for retrofit. Data will be analysed to find the correlations between occupants' behaviour and energy performance by using Statistical Package for the Social Sciences (SPSS). Research findings will help inform the design specifications of the innovative smart application. On the other hand, the review of Energy Efficiency Applications in the market has been undertaken to assess their successes and failures to help direct the new application developed by the study. Innovative aspects and methods for behavioural interventions will be thoroughly considered to inform the design specifications of the smart application.

## **Review and study of energy efficiency applications**

### ***Advanced Metering Infrastructure (AMI) and smart meters***

Due to the transition of the UK's energy network, the Advanced Metering Infrastructure (AMI) and smart meters has been rapidly developing. Through an experimental, large-scale case study, Gans et al (2013) monitored residential electricity consumption since April 2002 when the pre-payment meters were applied. Data collected between two different periods (with pre-payment meters and with advanced metering systems) show 11 to 17 percent decrease in energy consumption. The reason for this is that the new advanced metering system reveals real-time electricity usage to the occupants. It was also proven (Gans et al, 2013) that the occupants do respond to the provided information by using less energy with more careful behaviour. Similar results were supported by Stromback et al (2011), Wesley Schultz et al (2015) and Zhang et al (2016).

On the other hand, a few scholars (Rajagopalan et al., 2011; Schultz et al., 2015; Carroll et al., 2014; Hargreaves et al., 2017) disagree with the positive role that smart meters play in energy conservation. The general reasons include the feeling of invasion of privacy, increased energy bills due to smart meters and the lack of willingness to invest in the technology (Rajagopalan et al., 2011). In addition, Schultz et al (2015) proved that real-time feedback from Internal Home Displays (IHDs) has not helped reduce energy consumption effectively when IHDs only focus on energy consumption and costs. A seven percent electricity reduction was achieved only in the homes where IHDs were installed with comparison energy consumptions. This result has also been supported by studies by Carroll et al (2014) and Hargreaves et al (2017). Besides, it has been asserted (Hargreaves et al, 2017) that training

occupants and familiarising them with new technologies are important but time consuming. Based on the reviews above, the knowledge gaps have been identified below.

One of the reasons of BPG is that occupants' behavioural and socio-economic factors have not been thoroughly accounted for as those factors are typically unquantifiable (Sunikka-Blank and Galvin, 2016). More methodical efforts can be made in considering these 'hard-to-quantify' factors into the energy use reduction equation. For example, self-employed occupants will spend more time in their houses and use more energy than employed occupants in weekdays. Besides, occupants who prefer outdoor activities will spend less time in their homes and use less energy than others who prefer/ have to stay at home. As a result, the occupants' socio-demographic aspects, their energy use patterns and lifestyles need to be analysed and transformed into quantitative parameters for the energy consumption calculation and prediction. Besides, as real-time monitoring systems have become one of the well-established smart home technologies, to provide real-time behavioural suggestions to occupants becomes more plausible. In addition, due to the success of Homeselfe (a widely used energy saving application) in the USA, more effort can be made on developing a simplified energy mock-up application for occupants in the UK in order to increase their energy awareness and guidance to further reduce their energy bills following retrofit interventions.

### ***Energy Efficiency tools and applications in the domestic sector***

In the UK, the smart grid is a bi-directional energy system that does not only transmit energy demands from transmission centre to users, but also transmit energy feedback back to the transmission centre. The importance of this feedback mechanism has been realized for a few decades (Darby, 2010). As a bi-directional network, the development of a smart grid requires installations of smart devices in each home to effectively manage energy. The smart metering device can connect to an in-home display (IHD) for checking the detailed energy consumption and credit balance (The Cabinet Office et al, 2011). The smart meter captures real-time energy consumption of each household and transmits data back to energy companies, who are responsible for fitting the smart meters, for monitoring purposes. In addition, energy efficiency applications are developed based on the smart metering devices to help occupants understand their energy consumption patterns and save energy effectively (Zhang et al, 2016).

Several energy efficiency applications available in the market from major energy providers in the UK (British Gas, 2017; EDF Energy, 2017, E.ON UK, 2017, Npower, 2017, and Scottish Power, 2017) (such as British Gas app, EDF Energy app and E.ON app) and a number of applications developed from specializing companies (OVO Energy, 2017; apkpure, 2017; efergy engage, 2017 and Homeselfe, 2017) (such as efergy engage, OVO and Homeselfe) are compared and demonstrated in Table 1. The applications are evaluated against innovativeness and influenceon occupants. According to Figure 1, applications developed by energy companies have similarities in most of the aspects: user-friendly interfaces, simple operation, easy-to-understand graphics and illustrations, and improved customer services. Besides, energy saving advice is available in E.ON UK App, Npower App and YourEnergy App. It is noticed that only YourEnergy app can provide real-time energy monitoring and control for heating and hot water. Comparison scenarios, which has been proven as one of the most effective ways to reduce energy consumption, are only found in British Gas App and Npower app among all applications developed by energy companies. On the other hand, more innovative aspects can be found in the applications developed by specialist companies, such as energy saving advice and anticipative energy consumptions in Lotus Green Carbon

Calculator, efergy engage, OVO Energy and Homeselfe. Furthermore, the energy consumption comparisons are provided by Lotus Green Carbon Calculator and Homeselfe. In addition, the behavioural suggestions, which is not available in major energy companies applications, are provided by Lotus Green Carbon Calculator.

Table 1. Comparison of major energy efficiency apps in the current market (Source: Authors)

Features	British Gas	EDF Energy	E.ON	Npower	YourEnergy	OVO	Hive Active Heating	Carbon Calculator	efergy engage	Homeselfe
user-friendly interface	●	●	●	●	●	●	●	●	●	●
meter readings (manual)	●	●	●	●	●	●				
meter readings (automatical)									●	
real-time monitoring and					●		●		●	
visualized results	●	●	●	●	●	●	●	●	●	●
perspective use				●	●	●	●	●	●	●
energy consumption	●			●			●			●
energy-related behaviours								●		
energy saving		●	●	●			●			●
account management	●	●	●	●	●	●			●	
contact energy company	●	●	●	●	●	●	●		●	
switch supplier	●	●	●	●	●	●				
voice recognition						●	●			
rewards		●								

In the current study, both BES tools and energy efficiency applications are applied to achieve the aim of effectively reducing building energy consumption. The review of these tools provides fundamental and comprehensive knowledge on developing the innovative smart application. In general, energy efficiency applications provide more straightforward information and less in-depth professional knowledge than BES tools. Several issues have been found for its future development. For example, some innovative aspects have been found but have not been widely spread, such as comparison scenarios and behavioural suggestions. Besides, more effort can be made on providing real-time behavioural suggestions to occupants based on the existing energy monitoring system. Although energy consumption mock-up and audit has been proven successful (Barrett, 2016) in the USA, it has not been adopted in the UK, yet. In addition, a potential conflict has been identified by Hannon et al (2013) that energy efficiency applications developed by energy companies are not reliable. The reason for this is that energy suppliers raise income by selling more energy units to the occupants. Hence, they may not consider reducing energy consumptions if this compromises their profits. More efforts in tackling energy consumption reduction can be made by Energy Service Companies (ESCo) as they do not sell energy units.

## Discussion

In order to effectively tackle retrofit programme effectiveness and BPG, several issues have been discussed above, such as occupants' behaviour and energy efficiency tools. Although some limitations are found in different stages of the project, the research primarily focuses on how occupants operate their homes. The study attempts to provide possible solutions

for retrofit delivery by regulating occupants' behaviour in a more innovative and effective way rather than conventional education and training initiatives. Besides, the evaluation of energy efficiency and smart metering systems helped provide the preliminary step to develop the innovative smart application as a tangible deliverable of the research.

Table 2 The packages of the app and components required (Source: Authors)

Innovative Smart Phone Application	Components required
Instant Mode	Database: occupants' behaviour & energy performance
Potential Mode	Simplified simulation framework
	Comparison scenarios
	Visualized results
Both	User-friendly interface

Table 2 shows the proposed design specification of the innovative smart phone application. To provide real-time behavioural suggestions to the occupants, the correlations between energy performance and occupant's behaviour need to be thoroughly investigated. In addition, the experience feedback completed by occupants will also help to decide the options and of the application design specifications. Besides, the application also aims to provide an opportunity for occupants using energy simulation tools to increase their awareness and consequently increase retrofit project uptake rate through the energy 'mock-up' in the 'Potential Mode' of the application for those whose homes are due for retrofit. Without in-depth professional knowledge, occupants need an application with a simplified procedure, visualized results and user-friendly interface. Comparison scenarios is also incorporated into the application suite.

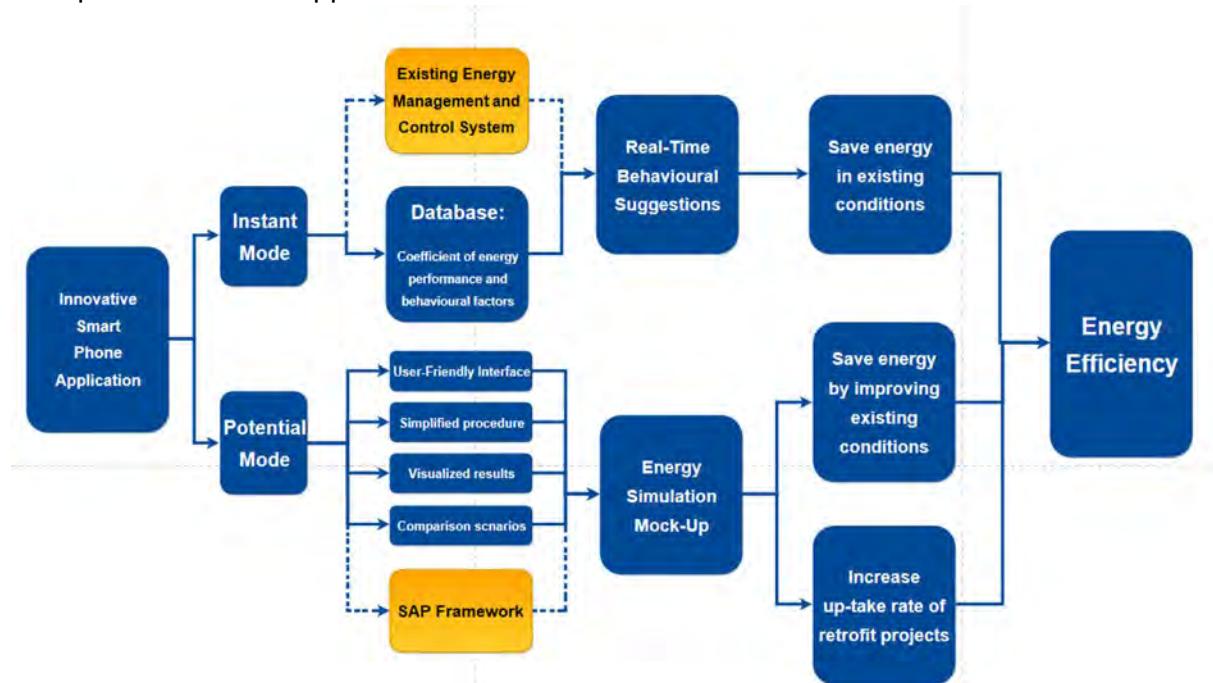


Figure 1. The proposed structure of the innovative smart phone application (Source: Authors)

As demonstrated in Figure 1, the application is split into 'Instant Mode' and 'Potential Mode'. As the tool is designed for occupants, its development will be based on simplified building energy simulations, user-friendly interface and visualized results. The real-time energy consumption will be monitored and advised with tailored behavioural advice

according to the real-time energy use patterns in the ‘Instant Mode’. On the other hand, occupants will be able to visualise and understand energy performance of their homes and potential savings by applying different retrofit approaches in the ‘Potential Mode’. The most appropriate retrofit approaches will be presented with straightforward results such as predicted energy savings, financial savings, and pay-back period for the investment. It is to be noticed that the ‘Instant Mode’ needs to be connected to smart meters. On the other hand, the ‘Potential Mode’ can be operated independently and will be available for all types of homes.

As discussed, occupants with different demographic and socio-economic status will differently operate their homes. The smart application will quantify these factors and automatically identify the appropriate range for energy consumption accordingly. From a list of particular energy-related behaviours, the most efficient pattern and range of energy consumption will be consolidated and suggested to the occupants when over-use of energy is detected.

## Conclusion

In this paper, a design specification of an innovative smart application to improve energy efficiency of homes has been presented. The concept developed from the interactions between occupants and smart metering systems with the aim to reduce the BPG by improving occupants’ energy consumption behaviour. The research starts with a comprehensive literature review to highlight some significant aspects. This will be followed by the investigation of the correlations between occupants’ behaviour and energy performance by collecting and analysing the questionnaires in two residential tower blocks in London.

The research provides an innovative perspective to facilitate the implementation and efficiency of the retrofit interventions through a ‘bottom up’ approach by focusing on the occupants. It allows occupants to run simplified energy simulation and provides them with real-time energy monitoring and advice on reducing energy consumption. Besides, the correlations between occupants’ behaviour and home energy performance helps to form the new function of real-time behavioural suggestions by connecting with smart meters. As a result, energy companies will have better understanding of the energy consumption patterns and behaviour of the homes due for retrofit. Appropriate interventions can be made from energy companies to investigate potential problems to be addressed. Consequently, the implementation of the innovative smart phone application will also help strengthen the relationship between energy management level and energy end users.

## References

- Barrett, D. (2016). Be Successful & Inspired. [online] Available at: <<http://danabarrett.com/success-owning-your-own-business/>> [Accessed 14 March 2017].
- Carroll, J., Lyons, S & Denny, E. (2014). Reducing household electricity demand through smart metering: The role of improved information about energy saving, *Energy Economics*, 45 (2014), pp234-243.
- Chaudhari, R. B., Dhande, D. P & Chaudhari, A. P. (2014). Home Energy Management System. In the International Conference on Modelling and Simulation in Engineering and Technology ICMSET-2014. Beijing, China. 15-16 Feb 2014. ICMSET: Beijing.
- Climate Change Act 2008. London: HMSO.
- Darby, S. (2010). Smart metering : what potential for householder engagement? *Building Research & Information*, (2010), 38 (5), 442-457.
- Department of Energy and Climate Change (DECC). (2009). *The UK low carbon transition plan*. London: National strategy for climate and energy, DECC.

Department of Energy and Climate Change (DECC). (2013). *UK Renewable Energy Roadmap*, London: DECC.

Dowson, M., Poole, A., Harrison, D & Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal, *Energy Policy*, 50 (2012), pp294 – 305.

Environmental Change Institute. (2005). *40% house*, Oxford: Environmental Change Institute, University of Oxford.

Gans, W., Alberini, A & Longo, A. (2013). Smart meter devices and the effect of feedback on residential electricity consumption: Evidence from a natural experiment in Northern Ireland, *Energy Economics*, 36 (2013), 729-743.

Gilbertson, J., Green, G., Ormandy, D & Thomson, H. (2008). Good housing and good health? A review and recommendations for housing and health practitioners. UK: A Sector Study Housing Corporation.

Greening, L. A., Greene, D. L and Difiglio, C. (2000). Energy efficiency and consumption — the rebound effect — a survey, *Energy Policy*, 28 (2000), 389-401.

Hadjri, K and Crozier, C. (2009). Post-occupancy evaluation: purpose, benefits and barriers. *Facilities*, Vol 27 Iss: 1/2, 21-33.

Hargreaves, T., Wilson, C & Hauxwell-Baldwin, R. (2017). Learning to live in a smart home, *Building Research & Information*, pp 1466-4321.

Khazzoom, J.D. (1980). Economic Implications of Mandated Efficiency in Standards for Household Appliances, *The Energy Journal*, 1 (4), 21-40.

Ma, Z., Cooper, P., Daly, D. & Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings*, 55, pp 889-902.

Preiser, W.F.E. (1989). *Building Evaluation*. New York, NY: Plenum.

Saunders, H. D. (1992). The Khazzoom-Brookes Postulate and Neoclassical Growth, *The Energy Journal*, 4 (1992), 131-148.

Sorrell, S and Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics*, 65 (3), 636-649.

Sunikka-Blank, M and Galvin, R. (2016). Irrational homeowners? How aesthetics and heritage values influence thermal retrofit decisions in the United Kingdom, *Energy Research and Social Science*, 11 (2016), 97-108.

Technology Strategy Board. (2012). *Retrofit Revealed, The Retrofit for the Future projects – data analyse report*. Swindon: Technology Strategy Board.

Technology Strategy Board. (2014). *RETROFIT FOR THE FUTURE – Reducing energy use in existing homes*. Swindon: Technology Strategy Board.

United Nations. (1992). *United Nations Framework Convention on Climate Change*. New York: United Nations.

United Nations. (1998). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. New York: United Nations.

Webber, P., Gouldson, A and Kerr, N. (2015). The impacts of household retrofit and domestic energy efficiency schemes: A large scale, ex post evaluation, *Energy Policy*, 84 (2015), 35-43.

Wesley Schultz, P., Estrada, M., Schmitt, J., Sokoloski, R & Silva-Send, N. (2015). Using in-home displays to provide smart meter feedback about household electricity consumption: A randomized control trial comparing kilowatts, cost, and social norms, *Energy*, 90(1), 351-358.

Zimring, C. M & Reizenstein, J. E. (1980). Post-Occupancy Evaluation: An Overview, *Environment and Behavior*, 12 (4), 429-450.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Embedding building performance evaluation in UK practice

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**Abstract:** Despite repeated efforts to foreground Building Performance Evaluation (BPE) in many countries, few have any policy or legislation in place to mandate BPE. Large scale voluntary efforts have failed to provide replicable templates. This paper critically reviews the various programmes and initiatives in the UK which have attempted to embed first POE, then BPE over the last twenty years, from a practice perspective. It examines the PROBE programme initiated in 1995 through to the Technology Strategy Board programme and the promise of Building Information Modelling linked with BPE and Soft Landings. Key findings are the lack of general engagement with the education sector as a key driver for BPE, as evidenced through the failure of a national BPE conference for Schools of Architecture in 2015 to translate its manifesto into practice, as well as the need for an engineering and architecture cultural meeting of minds through mutually developed processes. The paper then examines means by which BPE has been successfully embedded into practice directly, through deep organisational learning and knowledge transfer activities. Recommendations for these models to be replicated through professional institutions and other learning organisations in the UK are put forward in the Conclusion.

**Keywords:** Building performance evaluation, learning, practice, knowledge transfer

### Introduction - why has BPE not taken root in practice in the UK?

In his paper ‘Post-occupancy evaluation – where are you?, Ian Cooper (2001) speaks of ‘almost 40 years of continued neglect of POE...’(p.161). One helpful theoretical change that has taken place is the broadening of the field of Post-occupancy Evaluation (POE) into Building Performance Evaluation (BPE) as a ‘...a systematic and rigorous approach encompassing a number of activities including research, measurement, comparison, evaluation, and feedback that takes place through every phase of a building’s lifecycle...’(Mallory- Hill et al, 2012, p.3). Nearly two decades on from Cooper, however, there is still relatively little progress in mainstreaming BPE activity among built environment practitioners.

The twin origins of POE can be traced back to environmental psychology in the 1960’s, with its emphasis on the occupant experience, and the use of building science to monitor the physical performance of buildings in order to save energy in the 1970’s. However, with the discrediting in the 1980’s of environmental psychology as something overly deterministic, it was left to the newly emerging discipline of facilities management to pick up the reputation and work of POE (Cooper, 2001). As a professional response, the Royal British Institute of British Architects (RIBA) strategically recognised the need for gathering and disseminating ‘... information and experience on user requirements. ’ (ibid, p.159) and ‘...the study of buildings in use’ (ibid p.159) as early as 1962. This was then endorsed in 1965

by a new RIBA work stage M: Feedback which proposed that architects should inspect buildings two or three years after final completion as the ‘the most cost effective way of improving service to future clients’ (*ibid* p.159). Unfortunately this type of work was dropped by the RIBA in 1973 primarily because it was never aligned with a fixed payment mechanism and architects were reluctant to undertake POE studies without this financial commitment from the profession. The POE aspect of Part M was finally reinstated as the RIBA ‘Plan of Work Stage 7: In Use’, forty years later, but still without a specific mandatory fee attached to it. Another crucial omission by the RIBA was a failure to embed POE into the overall work programme earlier on as part of a strategic or project brief which would have completed the BPE feedback loop. Cost remains a key reason why both POE and BPE remain unembedded in general design practice in the UK and why the practice of BPE remains so disaggregated between different sectors (Figure 1). But is it any better elsewhere and are there other reasons why BPE is still not mainstream? What can be done about this today?

This paper critically reviews the various programmes and initiatives in the UK which have attempted to embed first POE, then BPE in non-domestic and domestic development processes over the last twenty years, both from a practice perspective and in a global context. It then examines the role that architectural education plays in relation to BPE progress before examining an alternative method of embedding BPE in practice through interdisciplinary knowledge transfer partnerships and deep learning, with some conclusive recommendations for taking BPE forward.

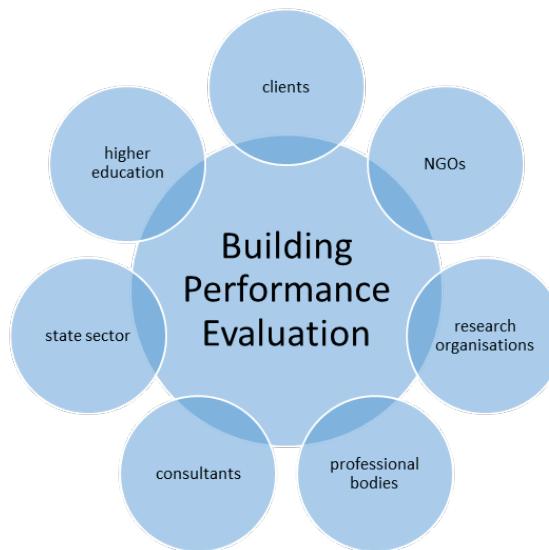


Figure 1. The disaggregated sectors of BPE.

### BPE practice across the globe

In Europe, there is a general understanding that POE studies are vital in terms of improving occupancy performance and reducing environmental impact. However, uptake is still extremely low, with only some local authorities or agencies mandating POE. Key factors for this include: low priority in terms of revenue v capital expenditure; localised cost cutting due to a disconnection between: procurement, provision and occupation; time constraints; no requirement from senior level; disconnection between projects preventing comparisons; and fear of poor performance (SCIN, 2012).

In the USA, a number of key research institutions are undertaking POE studies, but there is still no legislative requirement at either Federal or State level, despite an extensive survey of POE practice carried out by the Federal Facilities Council some time ago (2002). The General Service Administration, responsible for overseeing all 500,000 Federal buildings is committed to carrying out POE studies to validate best practice, but only on a sample basis (GSA, 2011). The story is similar in Australia and New Zealand, where despite having an excellent building performance rating system based on real data (NABERS, 2017), administered by the national government, participation remains voluntary apart from a mandatory energy use disclosure for commercial buildings over 1,000 sqm as of 1st July 2017.

There are various initiatives concerning BPE on other continents – both China (Zhu and Wu, 2013) and South America (Barbosa Villa and Walber Orenstein, 2013) are engaged in activities, but again there are no mandatory requirements across the board for doing a POE once a building is completed. Before exploring more deeply why BPE remains unembedded in practice and how this might be improved, it is worth briefly recapping the history of its development in the UK, as one country that has led on the development of a national BPE agenda.

### **BPE in the UK 1995-2017**

The government funded *PROBE* (Post-occupancy Review of Buildings and their Engineering) studies, which ran from 1995-2002, are generally recognised as the first systematic attempt to document the performance of new non-domestic buildings in the UK (Derbyshire, 2001). The twenty case studies relied on three combined POE activities – a preliminary questionnaire for the building manager, an occupant survey and an energy assessment – sometimes supplemented with an air tightness test. In 2005, the Building Research Establishment (BRE) set up the world's first *Innovation Park* in the UK with a number of new low or zero carbon homes designed to display innovative design, materials and technologies, one of which used new BPE methods (Stevenson and Rijal, 2010). Further BPE studies took place in the £17 million government funded UK *Retrofit for the Future* programme which ran from 2009 to 2013 to demonstrate and test the deep retrofitting of 86 existing homes (Gupta et al, 2015). The BRE also continued their interest in BPE, with the £6.4 million industry-led *AIM-C4* research project on innovative housing and product design (2010-14) informed by performance feedback (Gaze, 2014). Key actors lobbied the UK government for an £8 million national *BPE programme* (2010-15) with over 100 domestic and non-domestic BPE studies, published via the UK government's 'Digital Catapult' platform (<http://www.buildingdataexchange.org.uk/>). All of this suggests a steady stream of BPE activity in the UK, but it is just a drop in the ocean compared to the hundreds of thousands of buildings being erected each year in this country.

Currently, BPE activity in the UK has moved into the realm of Building Information Modelling (BIM), with the promise of linking up design input directly with facilities management feedback via object-related performance information. This is also closely related to a UK government mandate for its own stock of new buildings to be subject to a 'Soft Landings' process (<http://www.bimtaskgroup.org/wp-content/uploads/2013/02/The-Government-Soft-Landings-Policy-18022013.pdf>). This involves a careful proof testing with support at every stage of the building development to improve design, construction and handover, as well as a rigorous POE for at least two years after completion to fine tune performance and learn lessons for the next cycle (Way and Bordass, 2005). This process is

supposed to be powered by a Building Information Model to ensure that value is achieved in the operational lifecycle of an asset. To this end there is a UK BIM Task Group, but at this stage is it unclear whether BIM, as a state of the art, is ready to adopt BPE as mainstream, and the Government Soft Landings process itself appears to be stalled. Meanwhile, there are at least two fledging groups trying to establish a national NGO to promote BPE in the UK – one stemming from the initial government BPE programme, and one coming more from industry – but neither have government support at the moment, and BPE remains without a national champion. At the same time, the RIBA have produced a short POE/BPE ‘Primer’ document (RIBA, 2016) which shows good intent, but without an absolute requirement for BPE to be carried out by its members.

It is clear from the above, that although a number of BPE initiatives are underway in the UK, there is still no embedded mainstream activity going on, with only small groups operating semi-independently of each other, no single national body to promote BPE and relatively little government support. The situation, unfortunately, is little better in education, which is examined next.

### BPE in UK Education

The pedagogy of BPE still operates only in parts of the UK education sector, despite having been taught by enthusiasts for well over a decade in certain educational establishments such as the Architectural Association and Oxford Brookes University. In 2008, several eminent UK academics, organised a series of national workshops for all Schools of Architecture called ‘Designs on the Planet’ in recognition of the need to re-visit the technology curriculum within architectural education and provide better and shared investigative tools for students. The three workshops included a number of high profile events and speakers as well as participants from over 30 Schools of Architecture. It was generally concluded that ‘...there is a real need for evidence-based design approaches in education in order to improve building performance and lower their carbon emissions’. (Stevenson et al, 2009). From 2009 to 2012, another larger European Union programme called EDUCATE (*Environmental Design in University Curricula and Architectural Training in Europe*), with a budget of 1.65 million Euros, examined sustainable design in higher education through a consortium of seven leading European Universities. It received the support of the Chambers of Architects in all participating countries, and from international building professionals and of associations of educators and practitioners (<http://www.educate-sustainability.eu>). However, an examination of its outputs shows little evidence of embedding BPE in the curriculum as a holistic activity. Instead BPE is fragmented by being broken down into different aspects of monitoring and evaluation. POE as an educational topic is buried with a section entitled ‘Tools: Onsite Surveys and Measurements’. The simple ‘tool’ provided on POE is poorly referenced, adding little to the discourse.

As a final effort to revitalise the BPE agenda in education, the author organised a national BPE Conference in April 2015 under the auspices of the Standing Conference of Heads of Schools of Architecture in the UK. 44 Schools Architecture in UK – virtually all - registered representatives to attend the event. The culmination of the day was a manifesto to be forwarded to the RIBA Education Committee which simply stated: ‘This conference believes that integrating BPE within education is essential in order to: fulfill our responsibility to society ,exploit the potential for collaboration between academia, users, research, disciplines and professional practice in expanding the evidence base for affordable,

biodiverse rich, healthy, resource efficient building and urban design, supportive of communities.’. To obtain this degree of consensus from most Schools of Architecture is unusual and it was hoped it would surely change things, but two years later there is very little change evident. At the same time, the RIBA Validation Criteria remain silent on the need for either BPE or POE competencies in graduates, with only vague statements about graduates needing to understand ‘...the needs and aspirations of building users’ and ‘...the impact of buildings on the environment, and the precepts of sustainable design’ (GC5.1, GC5.2, RIBA, 2010). It is little wonder that so few Schools of Architecture in the UK teach POE or BPE techniques routinely. But perhaps there is hope elsewhere in another sector with practice initiatives that involve deeper and more iterative learning through knowledge transfer partnerships, as discussed next.

### **Using Knowledge Exchange to embed BPE in practice**

If BPE is not to be taught routinely in higher education, then it remains for practitioners to learn BPE from others in the best way possible. Key criteria for the Knowledge Exchange (KE) of BPE to be effective are:

- the perceived merits of the knowledge by the potential users
- the character and motivation of the knowledge provider picked up by the potential user and
- the social and political context in which the new knowledge and user operates (Young et al, 2016).

One way of enabling and embedding KE is through a Community of practice (CoP) which consists of a joint enterprise that is continually renegotiated by members of a group who are bound together through mutual engagement to develop a shared repertoire of communal resources over time (Wenger, 2010). The development of KE through and across CoPs is aided through the use of human ‘brokers’ who can translate, co-ordinate and align perspectives between CoPs using various tools and techniques. Brokers need enough legitimacy to be able to influence the development of a practice. They also require the ability to link practices by facilitating transactions between them and by introducing elements of practices to each other to enable learning (Wenger, 1998).

Effective BPE organisational learning can enable practices not only to improve their performance (single loop learning) but to question their assumptions (double loop learning) and open themselves up to intuitive new ways of being, knowing and doing (triple loop learning), starting with the leadership level. This requires BPE practice champions to work with (1) intuition, intention, and attention; (2) critical and strategic thinking; (3) vigilant and meaningful actions; and (4) impacts, outcomes, and feedback (Nicolaides and McCallum, 2013).

One example of this activity enabled a full-time Graduate Associate, with back up from two senior academics, to act as a BPE ‘broker’ when they undertook a two year Innovate UK Knowledge Transfer Partnership BPE project with Architype Architects, a leading sustainable design practice in the UK. This project resulted, not only in a number of significant BPE School studies but more importantly, in the co-development between the Senior Academics, the Graduate Associate and key practice ‘champions’ of new learning tools and processes for deeply embedding BPE in every aspect of the practice’s approach to producing architecture. This included an internal knowledge-sharing website using an open source

mediawiki framework with multiple plug-ins, as well as internal continuous professional development presentations (Pasquale et al, 2011). As a result, the practice now has BPE as part of its DNA as a new CoP, and uses multiple loop learning to feedback as well as feed forward their findings from their post-occupancy studies to improve all their design work. Critically, Archetype Architect build in BPE costs from the outset of any project, recognising the payback for the practice over time. Thus, BPE is now an inherent work stage activity in this example of best practice.

Another example of this type of BPE ‘brokering’ occurred when a well-known interdisciplinary practice based in the UK, Buro Happold Consulting Engineers, decided to collaborate with academics to develop a unique industry-based engineering doctorate programme, which the practice sponsored. A PhD student on this programme went on to undertake an in depth POE study while working in their Sustainability and Alternatives Technology (SAT) department in their London offices. The focus of the study was on the impact of occupant behaviour on the real-life performance of aspiring low energy/carbon buildings in the UK (Gill et al, 2010). Importantly, Buro Happold learnt significant lessons through this particular ‘broker’ who went onto provide similar services to one of the largest construction companies in the UK.

If BPE is to be fully embedded within practice, it is essential that interdisciplinary models are developed which can embrace all members of the design team as well as the client. While embedded Knowledge Transfer Partnerships and industry-based PhD studentships offer two ways forward for deeply embedding learning, a third model is needed that can transcend any professional boundaries associated with these two routes. The nascent BPE NGOs referred to earlier are both interested in promoting BPE consultants to work directly with clients. However, this does not develop the long term relationship that is necessary to change practice for good. A variation on this would be to promote a service that embeds interdisciplinary consultants for several years within a client organisation to allow the necessary trust for ‘brokering’ BPE and embedding it through multiple loop learning. All three models described here offer different ways to embed BPE in practice (Figure 2).

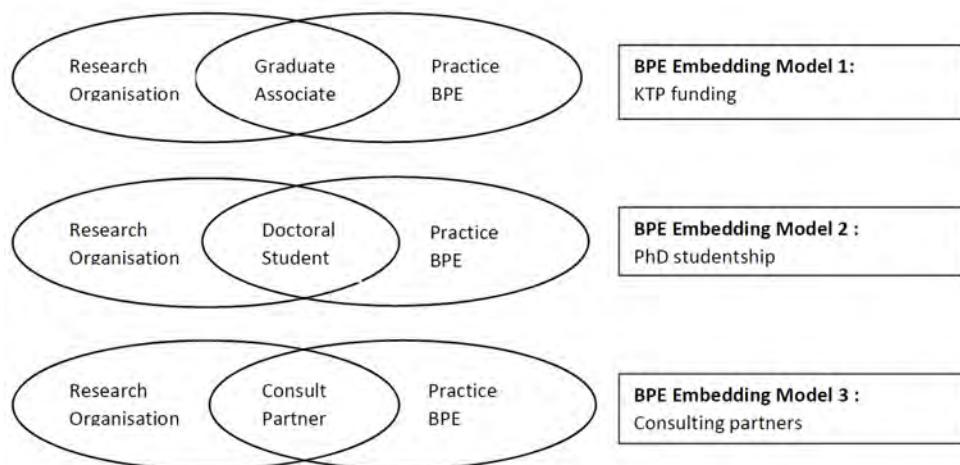


Figure 2. BPE deep learning models

This third interdisciplinary ‘consultancy’ BPE learning model can help to transcend the evidently different approaches towards BPE that come from architecture as a more social, qualitative and experimental culture and engineering as a culture that is typically more

quantitative and replicable, and allow the best of both worlds. One interesting initiative from the UK Royal Academy of Engineering has been the promotion of five year long Centres for Excellence in Sustainable Design which engage both architecture and engineering departments situated within four UK Universities, to develop a mutual understanding between these disciplines and enable interdisciplinary courses to be developed. It may well be that an initiative like this could embrace the BPE agenda which individual UK schools of architecture have collectively failed to grasp, as well as to bring the professional organisations of architecture and engineering together more in relation to this issue.

## Conclusion

This paper has presented a critical overview of the state of the art for BPE in the UK, situated in a global and historical context. It has demonstrated that at present BPE remains relatively untaught in UK higher education institutions and unembedded in practice, despite numerous government and educational initiatives. Deep ‘triple loop’ learning is required to challenge the status quo in existing practice at a more fundamental level, and three different models have been presented to show how such learning can be embedded over time through different knowledge transfer relationships to introduce new BPE CoPs within practice. There is a clear need to go beyond mere continuous practice development (CPD) training in BPE methods, in order to help practice understand the real value of BPE in developmental and financial terms. Any training has to be deeply embedded using practice ‘champions’ and ‘brokers’ who stay around long enough to ensure that a genuine and structural culture change takes place within the practice. Without this structural change, the BPE process can be easily lost when any BPE ‘champion’ or ‘broker’ leaves.

Establishing the underlying value of BPE remains a key area of challenge. This requires a stronger educational mandate from the various built environment professional bodies in terms of revising their CPD training and validation criteria to make knowledge and skills in BPE a much more explicit requirement, and to utilise the deep learning models proposed in this paper. It is not enough for there to be tacit assumption that this is contained within ‘understanding the needs of the user’ as stated in the RIBA validation criteria. Students in the built environment need to learn the concept of feedback from year one and this needs to be iterated throughout their learning programme using ‘triple loop’ learning. Feedback should be about how buildings really perform, and not only on how students think they should perform, through modelling, field measurements and social evaluations.

At the same time, it is doubtful that POE and BPE will ever become mainstream, given the past 60 years of its neglect in history, without governments mandating POE as part of the building regulatory framework. This in turn requires an attribution as to who in the building procurement and management process should pay for this activity – is it the client, the design team, or the occupants? Regulation could help to sort this out quite quickly, but it needs to be light touch and incisive, with the flexibility that comes with performance based regulation rather than settling on approved methods which need continuous updating. This could ensure that regulation allows BPE to continuously develop. It is hoped that this critical review and recommendations above may help to at least partly address the question by Cooper ‘POE – where are you?’

## References

- Barbosa Villa, S. and Walber Orenstein, S. (2013). *Housing Projects and Environmental Quality: Methodological Aspects of Post-occupancy evaluation and practical applications*. Sao Paulo: Oficina de Textos.
- Cooper, I. (2001). Post-occupancy evaluation – where are you? *Building Research & Information*, 29 (2), pp.158-163.
- Derbyshire, A. (2001). Probe in the UK context. *Building Research & Information*, 29 (2), pp. 79-84.
- Federal Facilities Council. (2002). *Learning from our Buildings: A State of the Practice Summary of Post Occupancy Evaluation*. Washington, DC: National Academies Press.
- Gaze, C. (2014). *Information Paper: Lessons from AIMC4 for cost-effective fabric-first low-energy housing*. Watford, UK: Building Research Establishment.
- General Service Administration (GSA) (2011). *Green Building Performance: a post-occupancy evaluation of 22 GSA buildings*. Washington, DC: US General Service Administration.
- Gill, Z.M., Tierney, M.J., Pegg, I. M. & Allan, N. (2010). Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research and Information*, 38 (5), pp. 491-508
- Gupta, R., Gregg, M., Passmore, S. & Stevens, G. (2015). Intent and outcomes from the Retrofit for the Future programme: key lessons. *Building Research & Information*, 43 (1), pp.1-18.
- Mallory-Hill, S., Preiser, W.F.E. & Watson, C. (Eds.) (2012). *Enhancing Building Performance*. Chichester: Wiley-Blackwell.
- National Australian Built Environment Rating System (NABERS). Retrieved from:  
<https://www.nabers.gov.au/> on 28<sup>th</sup> March 2017.
- Nicolaides, A. & McCallum, D.C. (2013). Inquiry in Action for Leadership in Turbulent Times: Exploring the Connection Between Transformative Learning and Adaptive Leadership. *Journal of Transformative Education*, 11(40), pp. 246-260
- Pasquale, L.A., Hancock, M. & Stevenson, F. (2011). *Embedding building performance evaluation in a medium-sized architectural practice: A soft landings approach*. PLEA 2011 - Architecture and Sustainable Development, Conference Proceedings of the 27th International Conference on Passive and Low Energy Architecture. pp 17-22
- Royal Institute of British Architects (RIBA) (2010). *Validation Criteria at Part 1 and Part 2*. Retrieved from:  
<https://www.architecture.com/files/ribaprofessionalservices/education/validation/ribavalidationcriteriafromseptember2011parts1,23.pdf>
- Royal Institute of British Architects (RIBA) (2016) *POE and BPE Primer*, RIBA, London: RIBA publishing. Retrieved from <https://www.architecture.com/RIBA/Professionalsupport/Assets/Files/RIBAPOEBPEPrimer.pdf>
- SCI-Network (SCIN) (2012). *Post Occupancy Evaluation: An insight into current POE-related policies and practices by European public authorities to drive sustainable construction and innovation*. Retrieved from <http://www.sci-network.eu/resources/reports/>
- Stevenson, F., Roberts, A., & Altomonte, S. (2009). *Designs on the Planet: a workshop series on architectural education and the challenges of climate change*. Proceedings of the 26th Conference on Passive and Low Energy Architecture, Quebec, 22-24<sup>th</sup> June.
- Stevenson, F., and Rijal, H.B. (2010). *Developing occupancy feedback from a prototype to improve housing production*. Building Research and Information, 38 (5), pp. 549-563.
- Way, M. and Bordass, B. (2005) Making feedback and post-occupancy evaluation routine 2: Soft landings – involving design and building teams in improving performance. *Building Research & Information*, 33 (4), pp.353-360.
- Wenger, E. (1998). *Communities of Practice: Learning, Meaning and Identity*. Cambridge: Cambridge University Press.
- Wenger, E. (2010). *Communities of practice and social learning systems: the career of a concept*. In Blackmore, C. Editor. *Communities of practice and Social Learning Systems*: Milton Keynes: Springer Verlag and the Open University. pp.125-143.
- Young, N., Corriveau, M., Nguyen, V. M., Cooke, S. J., & Hinch, S. G. (2016). How do potential knowledge users evaluate new claims about a contested resource? Problems of power and politics in knowledge exchange and mobilization. *Journal of Environmental Management*, 184, pp.380-388.
- Zhu, X.L. & Wu, S.X., (2013). Progress, challenges and prospects of POE in China. *Intelligent Buildings International*, 5(3), pp.181- 191.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Vulnerability and resilience in energy efficient homes: thermal response to heatwaves

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**Abstract:** Whilst people experience both external and internal temperatures, they are likely to spend most of their time indoors. During heatwaves, the majority of excess-deaths occur amongst the most vulnerable sections of the population. In addition, modern highly insulated homes can worsen this scenario since internal temperatures tend to respond more quickly to heat gains, leading to increased heat stress. This paper examines the vulnerability and resilience of low carbon homes to heatwaves. A monitoring study of four energy efficient homes in the UK has been carried out during the short heatwave which occurred in 2015. A close exploration of the variability of internal temperatures recorded with high resolution and in each room allows the areas of greatest risk to be mapped. These results are linked to occupants' responses. The analysis shows how building characteristics and ventilation can affect thermal conditions, and how design should take these into account.

**Keywords:** climate change, heatwaves, energy efficient homes, low carbon design, resilience.

### Introduction

Climate change is widely recognised as one of the greatest emerging humanitarian challenges of our time. Since the severe 2003 heatwave and associated excess deaths across Europe, the status of heatwaves has shifted from an interesting weather anomaly to precursors of potentially dangerous climate change; a 16% excess mortality was reported during that period, placing heatwaves as a major risk and number one among the natural hazards (i.e. tropical cyclones and related windstorms, hurricanes, tornadoes, lightning, droughts, and floods) of post-industrial societies (Poumadère et al. 2005). This situation is more alarming since climate change projections suggest that this excess mortality could rise to 5000 per year in 2080 (DCLG 2012).

There is no universal definition of heat waves. Heatwave is generally defined as a period of abnormally and uncomfortably hot and usually humid weather. In the UK, the Met Office adheres to a relativist definition "*a heatwave is an extended period of hot weather relative to the expected conditions of the area at that time of year*". On a tentative reconstruction around this theme, Perkins lists a number of definitions in which the duration of exposure to high temperatures and intensity are found in different degrees to

characterise heatwaves, making it difficult to compare changes at different regional scales (Perkins 2015).

The UK NHS heat wave plan (NHS 2015) triggers a heat wave alert when temperatures are '*high enough on at least two consecutive days to have significant effects*'. The Met Office National Severe Weather Warning Service (NSWWS) has defined day and night threshold temperatures by region, reflecting long term adaptation of the population to the local climate. For homes, the focus of this study, the relevant regions are the Midlands and Yorkshire, which both have external temperatures threshold values of 15°C night (min) and 30°C/29°C day (max) respectively.

By investigating the relationship between heat and mortality for a 21 year period, Armstrong et al. concluded that a growth in heat-related deaths begins at a relatively low mean (of summer daily maximum) external temperature (19.5°C in Yorkshire & Humberside and 20.3°C in East Midlands), and have provided a list of threshold temperatures for heat effects, i.e. 22.2°C for Yorkshire and 23.0 °C for the Midlands (Armstrong et al. 2011).

There is clearly a link between internal and external temperatures, but this is not well understood due to a lack of data (Dengel & Swainson 2012). During heat waves, people experience both external and internal temperatures, but they are likely to spend most of their time indoors. Furthermore, the majority of excess-deaths during a heatwave occur amongst the elderly, who are known to spend an even higher proportion of time indoors than the general population (Poumadère et al. 2005).

The UK government has set up a binding emissions reduction targets requiring a substantial reduction of emissions from buildings with consequential substantial changes to the UK building regulations, resulting in new homes with significantly increased levels of thermal insulation and much higher levels of airtightness (HM 2013). However, energy efficient homes are prone to overheat (Toledo et al. 2016) because such homes respond quickly to heat gains. As a result, internal temperatures tend to be higher, especially during evenings. This may be exacerbated by a lack of thermal mass –common in modern homes– and solar protection or poor ventilation through windows. Where mechanical ventilation with heat recovery (MVHR) is employed a lack of summer by-pass can slow the heat removal. Night cooling would also be ineffective with the 1.5 air changes per hour (ACH) provided with MVHR (at least 10ACH are required to provide night ventilation) (Orme & Palmer 2003).

There is only limited evidence available about the response of internal temperatures to heatwaves (Dengel & Swainson 2012), especially when considering the energy efficient housing stock. A monitoring study of 9 traditional dwellings located in Manchester and London, Wright et al. found that, during the August 2003 heatwave, when the daily average external temperatures were exceptionally high for the UK (20°C), dwellings with thermal mass exposed showed internal temperatures being up to 5K higher than the (night) outdoor air temperature, in both Manchester and London, suggesting that thermal mass capacity may restrict the effectiveness of night ventilation to provide comfort at night (Wright et al. 2005). From a survey of 101 homes, Mavrogianni reported that on both typical and warm days, respondents opened the windows mostly due to the need of fresh air rather than high indoor temperatures; respondents stated that they do not usually open the windows due to concerns about security and high external noise levels (Mavrogianni et al. 2016).

From monitoring 25 energy efficient dwellings during three summers (2011, 2012, 2013), Tabatabaei Sameni et al. found no direct relationship between external environmental factors and indoor overheating, and that occupant behaviour is the most

important factor (Tabatabaei Sameni et al. 2015). A recent report presented by Innovate UK (Jason Palmer, Daniel Godoy-Shimizu 2016) showed that one Passivhaus dwelling was reported to have exceeded 28°C for 9% of the summer and exceeded 25°C for one-fifth of the summer, presumed to be due to lack of window opening. However, leaving the windows closed and letting the MVHR "do the job" is the instruction provided to the residents, even though window ventilation in summer is part of the Passivhaus design.

The research presented here aims to contribute to this body of knowledge by presenting data from four energy efficient homes across the UK monitored during the short heatwave experienced in 2015. The aims of this paper are (a) to provide a graphical description and statistics on the response of 4 energy efficient homes to the 2015 heatwave; (b) to examine the influence of building characteristics on internal temperatures; and (c) to examine the influence of user behaviour on internal temperatures (the variability of internal temperatures recorded will be linked to occupants' responses).

## Methods

Longitudinal data were collected using Onset HOBO Pendant Temperature Loggers placed in every room of the each house monitored during summer 2015 (see table 1). The sensors recorded air temperature values at 10 min intervals. These measurements were complemented by an occupant questionnaire aimed at collecting feedback about the effectiveness of new highly efficient designs, as well as to collect data about occupants' behaviour, control, and comfort sensation, in order to relate these to the temperature measurements in their homes.

Table 1. Overview of case studies homes.

<b>House code</b>	<b>House type &amp; location</b>	<b>U-value ext. walls (W/m<sup>2</sup>.K)</b>	<b>Thermal mass</b>	<b>Orientation (solar gain)</b>	<b>Ventilation type</b>	<b>Cross ventilation</b>	<b>Solar control</b>
<b>UK51</b>	Refurbished terrace Leicester (UK)	0.12	NO	E-W	MVHR (no summer by-pass)	YES	Only internal blinds on Velux windows
<b>UK52</b>	New detached bungalow Sandiacre (UK)	0.09	NO	N-S	MVHR (no summer by-pass)	YES	Not provided
<b>UK54</b>	New terrace York (UK)	0.19	YES	N-S	MV	YES	Only internal blinds on Velux windows
<b>UK55</b>	New detached York (UK)	0.19	YES	E-W	MVHR (no summer by-pass)	YES	Only internal blinds on Velux windows

There was a brief but sharp heat wave peaking at above 30°C on 1 July 2015 in England, coinciding with high solar gain and high humidity. The period chosen for this analysis closely corresponds to the generic definition of a heatwave "*period of abnormally and uncomfortably hot and usually humid weather*" and satisfies two conditions: (a) when daily average external temperatures were above 20°C and (b) when the NSWWS threshold peak temperature was reached. Figure 1 shows a graphical representation of this period, from 28 June to 3<sup>rd</sup> July 2015.

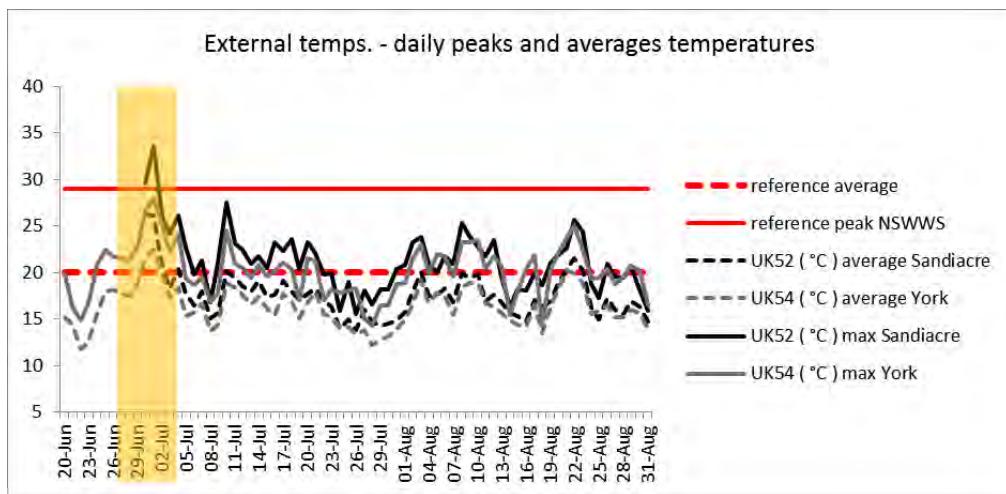


Figure 1. External temperatures recorded in case study homes, evidencing the period considered as heatwave.

## Results and discussion

### **Descriptive statistics**

Figure 2 shows the median, interquartile range (box) and max/min values over the hot period. In general the internal/external median differences lie between 4K and 8K. Also, noticeable are two extreme values, circled in red: (a) the room in UK52 containing the water tank for domestic hot water, and (b) the East facing sunspace in UK55 with no solar protection. Both spaces are located within the thermal envelope of the homes and would be expected to contribute to overall heat gains.

For house UK51 (Passivhaus refurbished terrace, MVHR), the highest temperature ranges were found in bedroom 2, located in the 2<sup>nd</sup> floor loft conversion, and provided with two windows in the slope of the roof facing East and West. Here temperatures are shown to be too high for comfortable sleep during the heatwave (it was noted that occupants of this room slept in the living room on a lower floor during these days). During the 1<sup>st</sup> July 2015, in house UK51 all room temperatures varied between 25-34°C (most rooms between 25-30°C). When external temperatures were at the lowest, around 5:00-6:00 am, internal temperatures were 3-6K higher. During the morning, internal temperatures were found to be fairly stable and below external temperatures, except bedroom 2.

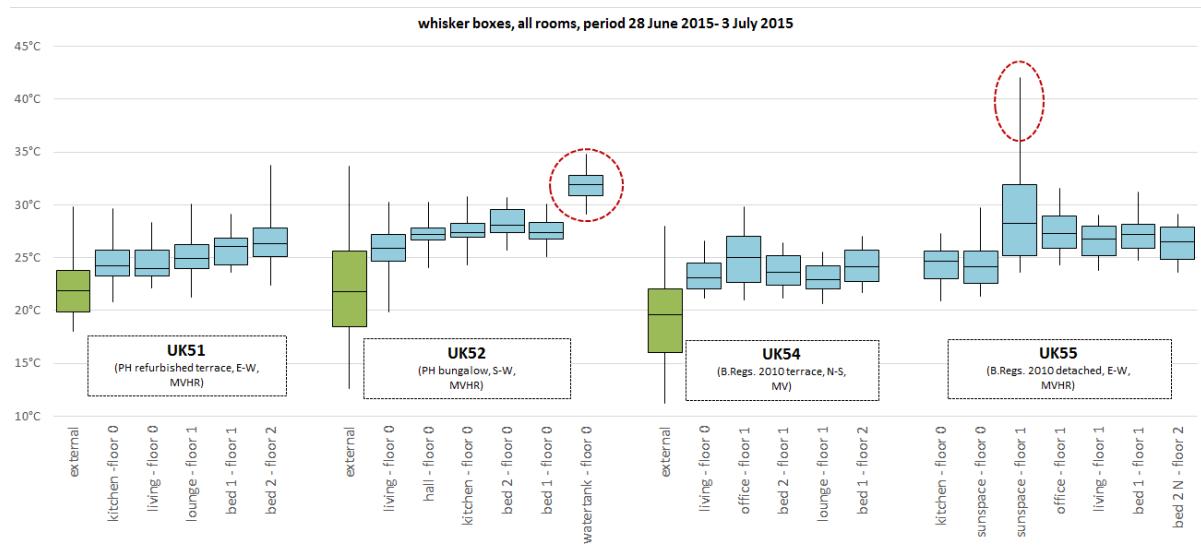


Figure 2. Box and whiskers plot, from 28 June 2015 until 3 July 2015.

House UK52 (lightweight Passivhaus bungalow, MVHR) showed less variation compared to the other homes. The living room was found to be the coolest space of this house, presumably due to the provision of cross ventilation within that room. The bedroom temperatures however were always above 25°C. The occupant reported leaving the windows slightly open (in a lockable position) during the daytime. As house UK52 is a bungalow with lightweight construction, it was expected that temperatures would fall quickly as the night progressed; however, that was not the case. This could be due to the MVHR having no summer bypass or due to window being closed during sleep hours (as reported by the occupant). Supporting the view that small volumes of fresh air do not provide significant night cooling, as previously reported by Orme & Palmer (2003). During the 1<sup>st</sup> July 2015, in house UK52, all room temperatures were between 23-31°C. When external temperatures were at the lowest, around 5:00 am, internal temperatures were 8-10K higher. All room temperatures increased as the day progressed.

	Descriptive Statistics						
	N	Range	Minimum	Maximum	°C Mean	Std. Deviation	Variance
°C UK51 living (f 0-E)	144	6.2	22.1	28.4	24.590	1.6004	2.561
°C UK51 bed 1 (f 1-E)	144	5.6	23.6	29.2	25.891	1.5741	2.478
°C UK51 bed 2 (f 2 -E&W)	144	11.3	22.4	33.7	26.728	2.5676	6.593
°C UK52 living (f 0/N&W)	82	10.4	19.9	30.3	25.894	2.3023	5.301
°C UK52 bed 2 (f 0/S)	82	5.0	25.7	30.7	28.492	1.3245	1.754
°C UK52 bed 1 (f 0/S)	82	4.9	25.1	30.1	27.615	1.1622	1.351
°C UK54 living (f 0/N&S)	144	5.4	21.2	26.5	23.260	1.3362	1.786
°C UK54 bed 2 (f 1/N&S)	144	5.2	21.2	26.4	23.749	1.5116	2.285
°C UK54 bed 1 (f 2/ N&S)	144	5.3	21.7	27.0	24.248	1.5115	2.285
°C UK55 living (f 1/S&W)	144	5.3	23.8	29.1	26.664	1.4869	2.211
°C UK55 bed 1(f 1/W)	144	6.4	24.8	31.2	27.142	1.5254	2.327
°C UK55 bed 2 N (f 2/W)	144	5.6	23.6	29.2	26.360	1.6431	2.700

Figure 3. Descriptive statistics.

House UK54 (highly insulated with thermal mass exposed, naturally ventilated) performed the best of the four case study houses. Unlike the other homes, this house is the only one managed using natural ventilation alone (extract mechanical ventilation is available, but the occupant had turned this off for the summer). During the 1<sup>st</sup> July 2015, in house UK54, all room temperatures were between 21-30°C (most rooms between 23-26°C). When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 5-10K higher. The office, with south facing sloping roof windows, is the only room with daytime temperatures above external temperatures. All the other rooms maintained lower temperatures during external peak times.

In house UK55 (highly insulated with thermal mass exposed, MVHR), where most windows were kept close during the heatwave, and MVHR was 'left to do the job', the biggest internal-external median difference was found, suggesting that MVHR only ventilation results in inadequate purge ventilation resulting in the build-up of internal temperatures. The coolest room was found to be the kitchen, which was managed by opening window. In most spaces overheating appears to be the result of uncontrolled morning solar gains and lack of windows opening, confirmed by the occupant's questionnaire. During the 1<sup>st</sup> July 2015, in house UK55, most room temperatures were between 25-30°C. When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 10-15K higher. The East facing sunspace with no solar gain control presented the highest peak temperatures, with a difference with external temperatures up to 18K. When external temperatures peaked in the afternoon, the west

facing bedroom exceeded 30°C. The high night time temperatures in all rooms suggest that no night cooling was applied.

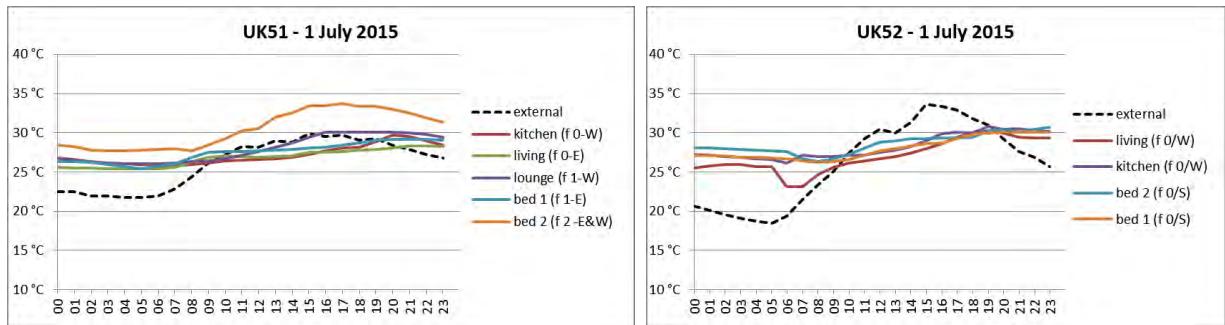


Figure 4. Temperatures swing during the 1<sup>st</sup> July 2015 in house UK51 (left) and in house UK52 (right).

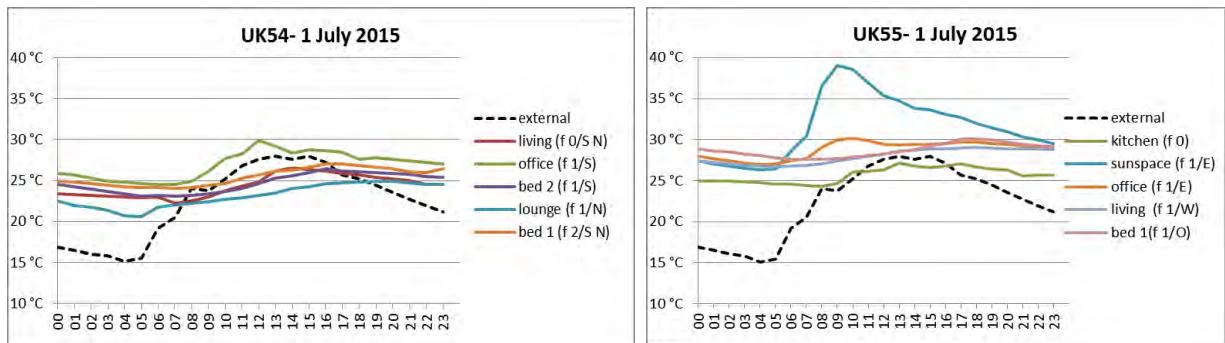


Figure 5. Temperatures swing during the 1<sup>st</sup> July 2015 in house UK54 (left) and in house UK55 (right).

### Lag

It can be seen in figure 6, which include temperatures in the days before and after the heatwave, that while external temperatures were reduced from 2<sup>nd</sup> July 2015 onwards, the high internal temperatures were maintained in all the homes for several days. In house UK51 (retrofitted/MVHR) and in house UK52 (lightweight/MVHR) the main bedroom temperatures were above 25°C for more than three days after the heatwave. In house UK54 (thermal mass/natural ventilation) the main bedroom temperatures were below the peak day external temperature but above the peak day external temperature on the following day. A similar pattern was observed in house UK55 (thermal mass/MVHR), but 3-4K higher. However, in house UK55 the main bedroom temperatures were above the peak day external temperature at all times.

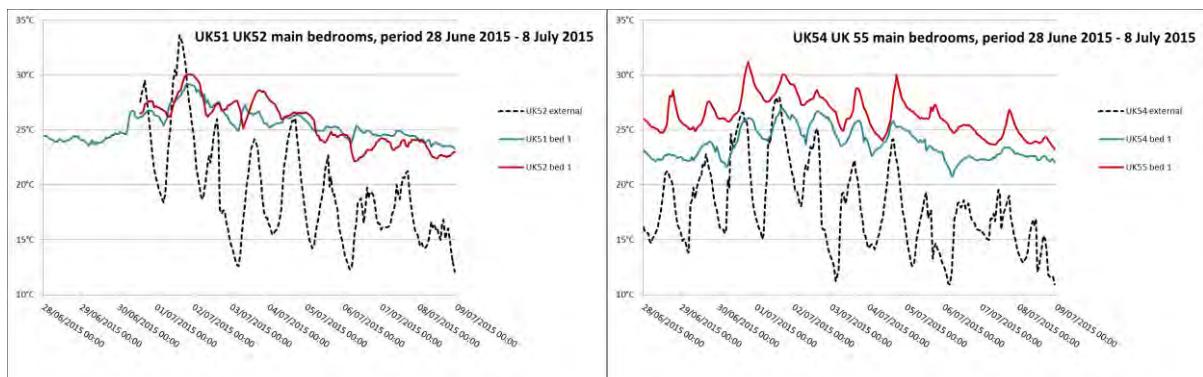


Figure 6. Temp. swing from 28<sup>th</sup> June to 9<sup>th</sup> July 2015: houses UK51 and UK52 (left) and UK54 and UK55 (right).

## **Resilience**

All habitable rooms' data has been examined to look for cooler rooms within the houses. Of the four homes examined, house UK54 (thermal mass, North-South orientation) had the lowest maximum and the lowest average temperatures during the heatwave. The coolest room was the north facing lounge at the first floor where temperatures never exceeded 26°C. House UK55 (thermal mass, East-West orientation) was found to perform the worst, though it provides with the second most resilient room, this room is the kitchen, located in the ground floor and with little or no solar gain, and, importantly, known to be naturally ventilated. Interestingly, UK52 (lightweight) and UK55 (heavyweight) bedrooms average temperatures were very similar. Both homes employ MVHR, but UK52 occupant incorporated additional ventilation through window opening. This could provide evidence that lightweight dwellings are at most risk of heat stress during heatwaves.

In general, bedroom temperatures tend to be higher than living areas' temperatures: (a) in the refurbished terrace house UK51 this could be attributed to the stacking effect and solar gains; (b) in the Passivhaus bungalow UK52 this could be attributable to the availability of crossed ventilation in the living room; (c) in UK54 and UK55 this could be attributable to both the previous reasons and additionally to the generous dimensions of the living rooms.

Finally, there is an interesting effect that the ventilation strategy has with the thermal performance during heatwaves: within the four case studies, homes that managed the ventilation via MVHR (UK55) and MVHR combined with window opening (mixed mode ventilation) (UK51, UK52) showed the highest temperatures. Also, the highest temperatures in the dwelling that managed the ventilation via window opening only (natural ventilation) (UK54) were the same as the lowest temperatures with MVHR.

## **Conclusions**

This paper has provided a graphical and statistical description of the performance of four energy efficient homes across UK during the 2015 heatwave. The findings show that internal temperatures across these homes were uncomfortably high, except for UK54.

The persistence of high indoor temperatures after the peak day (i.e. four days in some cases) suggests that highly insulated homes might be considered as posing an increased risk to health, under certain layout, typology, and orientations. The study also shows that, in a non-dense urban area, such as York, thermal mass in highly insulated homes can provide effective night cooling, if the proper orientation and ventilation strategy is in place (among the two heavyweight homes, the one with no MVHR and natural ventilation performed much better).

At times, some of the rooms became unusable and occupants had to relocate to another room. This option is not always available in homes with a higher occupancy density. Therefore designers of energy efficient homes should incorporate this experience in their designs, providing spaces with a thermal variability that will allow for thermal relief during heatwaves. This way the design of energy efficient homes could also be resilient to heatwaves. It has also been found that occupants adapt to their environments (all occupants ventilated at least one room). However, as shown by house UK52 (lightweight bungalow Passivhaus), user behaviour alone may not be sufficient to adapt to heatwave conditions. In house UK52 external shading and secure night ventilation were not available; and these should be the bare minimum that energy efficient design should provide. This capability of designing environments able to adapt (or to let people adapt) to extreme

weather events constitutes the key to move away from vulnerable designs to resilient and thriving designs.

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## References

- Armstrong, B.G. et al., 2011. Association of mortality with high temperatures in a temperate climate: England and Wales. *Journal of Epidemiology & Community Health*, 65(4), pp.340–345. Available at: <http://jech.bmjjournals.org/cgi/doi/10.1136/jech.2009.093161>.
- Bezaee, A., Lomas, K.J. & Firth, S.K., 2013. National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, 65, pp.1–17.
- DCLG, 2012. *Investigation into Overheating in Homes: Literature Review*, London: Crown Copyright.
- Dengel, A. & Swainson, M., 2012. *Overheating in new homes. A review of the evidence*, Milton Keynes: NHBC Foundation.
- HM, 2013. The Building Regulations 2010, approved document L1A: Conservation of fuel and power in new dwellings, edition 2013.
- Jason Palmer, Daniel Godoy-Shimizu, A.T. and I.M., 2016. Building Performance Evaluation Programme : Findings from domestic projects Making reality match design., (January).
- Killip, G., 2005. Built fabric & building regulations. Background material F 40% House project.
- Mavrogianni, A. et al., 2016. Inhabitant actions and summer overheating risk in London dwellings. *Building Research and Information*, Under review(August).
- NHS, 2015. *Heatwave Plan for England*.
- Orme, M. & Palmer, J., 2003. Control of overheating in future housing - design guidance for low energy strategies. , p.48.
- Perkins, S.E., 2015. A review on the scientific understanding of heatwaves-Their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research*, 164–165, pp.242–267.
- Poumadère, M. et al., 2005. The 2003 heat wave in France: Dangerous climate change here and now. *Risk Analysis*, 25(6), pp.1483–1494.
- Tabatabaei Sameni, S.M. et al., 2015. Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, pp.222–235.
- Toledo, L., Cropper, P.C. & Wright, A.J., 2016. Unintended consequences of sustainable architecture : Evaluating overheating risks in new dwellings. In *PLEA 2016 Los Angeles - 32th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments*. Available at: <http://www.plea2016.org/index.html>.
- Wright, A., Young, A. & Natarajan, S., 2005. Dwelling temperatures and comfort during the August 2003 heat wave. *Building Services Engineering Research and Technology*, 26(4), pp.285–300. Available at: <http://bse.sagepub.com/content/26/4/285.short>.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## How do you live? Evaluation of environmental quality of housing in Uberlândia (Brazil)

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**Abstract:** This paper presents part of the research that aims to develop a post-occupancy evaluation (POE) interactive system over digital media to identify the quality of the houses under investigation. The feasibility of this interactive system is been tested in case studies in the city of Uberlândia (Brazil) and may fundament its future replication in other cities. This paper focuses on the theoretical foundation of the research as well as on its environmental approach, considering the strategies used to verify the environmental quality of housing within the proposed evaluation system. Besides energy efficiency and environmental performance of housing, this research was interested to identify the behaviour of dwellers regarding the use of different natural resources, analysing their habits and actions. Preliminary results indicate that the use of technologies and digital resources can minimize some of the frequent problems that occur in traditional POE studies, as they increase the efficiency of evaluation results, reduce the execution time and the costs of researches, and increase the interest of the questionnaire respondents, especially concerning issues related to the sustainability of the built environment.

**Keywords:** Post-occupancy evaluation; Technology innovation; Digital interfaces; Environmental quality; Sustainability.

### Introduction

With a large array of possibilities in research, the theme of “housing” has been studied with varying approaches and broken down into extracts. Even though the perspective of each analysis varies, they conjoin on the understanding that “living” represents a fundamental act in human existence. The psychic importance of the house in the constitution of the individual is emphasized by Penzim (2007), indicating that the house brings the possibility of synthesis of life for “man”, setting itself as a shelter for different human activities.

Apart from the condition of this protective space as a shelter, housing also represents a space for private life, permitting the interdependent establishment of relationships and, at the same time, respect for intimacy (Kunze; Conciani, 2004). However, while living spaces are individual, they present a collective dimension: each member of the family occupies a single enclosure and, in addition to this, the people of this family interact and socialize with the neighbourhood, the district and the city (Araújo, 2005). Because of this, the analysis of the house, shelter of “living”, should always be related to the investigation on the physical territory and the environment in which it is situated.

To ascertain "How do you live?", in the scope of the research presented here, is seeking to learn the multiple meanings of "to live" within the following dimensions: physical, behavioural and urban insertion. Considering the importance of living to the human being, the necessity of knowing how the residents of our cities are being sheltered is justified. In other words, it is important to evaluate the housing quality.

In this context, observe that Brazilian cities receive hundreds of housing units per year, implemented by public and private agents, that contradict basic housing principles: aspects of functionality, spaciousness and privacy are generally attended with minimum attention - as can be proved in studies of Post-Occupancy Evaluation (Amore; Shimbo; Rufino, 2015; Villa; Saramago; Garcia, 2015). This situation notably intensified in the first decade of the 21st century, when there was a significant increase in the access to credit, pressing the demand for different typologies of housing units around the country.

With this in mind, Post-Occupancy Evaluation (POE) is a fundamental tool in the evaluation of the quality in Brazilian housing production. The relevance of POE for the attainment of the level of quality in the architecture project is already consolidated enough for use in other studies in the field of civil construction (Voordt; Wegen, 2013; Villa; Ornstein, 2013). The role of management of the project process, in which POE is inserted, from the service received to the quality of the built spaces, notably in housing, were also amply researched (Mallory-Hill, Preiser, Watson, 2012; Kowaltowski et al., 2013).

On the other hand, apart from the effort to found the quality of housing, observe that many studies are limited, in as such that the works often focalize certain aspects that configure the quality of housing. This is the case in the researches that focus on the systems related to environmental comfort and the energy efficiency of the housing units, of which, initially, centered on defining parameters of performance of these systems, whereas more recent studies have shown the necessity of revising the parameters of evaluation proposed initially.

In Holland, for example, it was concluded that more efficient technology, in general, reduce the price of energy services, motivating a change in the behaviour of users, increasing energy consumption (Visscher; Werf; Voordt, 2013). In the United Kingdom, according to Stevenson (2013), the problem centers on the absence of more concise studies on the usability of low carbon technologies. Therefore, when these technologies do not attend the intended purpose - presenting incorrect installation and operation - a potential negative reaction is generated towards their adoption on the part of the residents. Thus, it has been noted that environmental measures should be related to the daily life of the residents and their expectations (Martincigh et al., 2016), even in the cases of high performance buildings (Yudelson, 2016).

Thus, this research reinforces the need to identify the role of the residents in the reduction of environmental impacts, by analyzing their habits and actions. It also aims to contribute to the current discussion on the way to live in an opportune moment, given the quantity of housing enterprises launched daily in Brazil. Therefore it has become necessary to consider the quality of such production, certifying how they meet the following points: (i) the technical specifications of used construction materials and systems to guarantee the comfort of residential units; (ii) the ways of living of different family, social and cultural profiles, which influencing their actions on the environment; and (iii) the urban impacts generated by the implantation of the houses.

## **Objectives of the research**

This research aims at developing a POE interactive system through digital media that permits to identify the quality of the housing. The feasibility of this interactive system has been tested by case studies in the city of Uberlândia (Brazil) and may fundament its future replication in other cities. The methodology of POE through digital media focuses on the functional, behavioural and environmental aspects of housing and is organized in a stage that begins with the residents' personal details and goes up to the evaluation of the residential unit itself. This work focuses specifically on the environmental quality of the proposed evaluation system.

## **Methodology of the research**

Methodologically, the questionnaire is structured in the: (i) bibliographical research (internet and libraries) about typologies, aspects and evaluation of living with the aim to establish the current state of the art of the proposed thematic; (ii) categorization and definition of the main attributes approached in the evaluation; (iii) identification of the limits and extracts of the evaluation system to be developed from the definitions above, characterizing and defining their parts, tools, workings and also objectives; (iv) development of working prototypes of the interactive POE system through digital media (PCs); (v) application of tests for the tools of the system using functional prototypes on the population of Uberlândia; (vi) development of the interactive POE system through digital media (internet, e-tablets and smartphones); (vii) application of definitive tests of the interactive POE system through digital media on different types of housing in the city of Uberlândia, with the aim of its future replication throughout national territory; and (viii) availability of the interactive POE system through digital media to the community.

With the specific objective of evaluating the environmental housing quality and to support the development of the evaluation system through digital media, methodologically, the questionnaire was structured by: (i) the discrimination of the evaluation attributes of the housing in view of environmental quality; (ii) the elaboration of the questions to be inserted into the proposed evaluation system; (iii) the creation of educational feedback on the questions for the users; (iv) support for the development of the evaluation system; (v) testing the evaluation system in case studies in Uberlândia; and (vi) the organization of the database for the environmental quality for living.

Thus, the first stage of the research involved the consultation of various sources to identify and characterize the attributes of the housing environmental quality evaluation on different scales (physical, behavioural and urban insertion). With these attributes defined, the questions to be inserted into the evaluation system were elaborated (second stage), therefore identifying the possibility to inform the respondents, throughout the questionnaire, about their behaviour - in other words, to create educational feedback (third stage).

For the fourth stage, the work continues the studies developed in the scope of the group “[MORA] pesquisa em habitação”<sup>1</sup> of the Faculty of Architecture and Urbanism and Design at the Federal University of Uberlândia, focusing exactly on Post-Occupancy Evaluation methodologies and digital interfaces, in particular the DIGITAL POE research, which proposes software and an interface destined for the evaluation of apartment

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<sup>1</sup> <https://morahabitacao.com>

buildings using digital tools (e-tablets, web)<sup>2</sup>. Although, the work presented here has extended the use of the tools developed, in the sense that to elaborate a system that can be employed in different typologies of housing. Therefore, parallel to the definition of the attributes in the evaluation, another team developed the graphic design of the new system, as well as the digital interface. Thus, the fourth stage gave support to the development of the tools for the evaluation system through digital media (e-tablets, web) as in the aspects related to sustainability and the environmental comfort - considering, therefore, the results of the previous stages.

After the development of the interactive system, the next stage of the research consisted of applying it to the users of varied housing typologies in Uberlândia to test its viability. Such an application, being work in progress, can indicate the necessity for adjustments to be made as much in the evaluation tool being developed as in the actual questions being asked. Finally, from the participation of different users in the evaluation of housing quality in Uberlândia, it will be possible to organize a database of different aspects of living, including those which are more specifically related to the environmental quality of the housing (sixth stage). It is intended that the systematization of the results generate informative graphs and schemes.

## **Results and discussion**

To better analyze the results obtained through the research, they were organized into the methodological stages described above: attributes for the evaluation of environmental quality, elaboration of questions and feedback for the POE and the interactive system for the evaluation of housing quality through digital media.

### ***Attributes for the evaluation of environmental quality***

Previous researches were used, as a reference, for the determination of the attributes to be used in the evaluation (Villa; Saramago; Garcia, 2015; Villa et al., 2016), which also dealt with the application of POE in housing to verify environmental quality, although in other extracts (apartment buildings or/and social housing). Therefore, considering the works that have been developed previously, the reach of the current investigation has been extended aiming at the contemplation of different housing typologies (horizontal or vertical; in closed gate communities or allotted space).

Furthermore, the analysis scales in the questionnaire focus on: physical (technical and constructional aspects, attesting the environmental quality of the residential units, especially in terms of comfort), behavioural (habits and actions of the users that have an impact on the way they live) and urban insertion (impacts derived from the implantation of housing in the city). It was considered that the environmental approach of the research should be in balance with the analysis of functionality, also present in the general research and responsible for questions relative to the ways of living (uses and activities present in the domestic environment), of the family profiles and the spatial necessities of the residents.

Thus, from the different data collected, the evaluation attributes were categorized into the following aspects: environmental comfort (thermal, lighting and acoustic), water and energy consumption, waste collection and disposal, consumption of organic food, vegetation and urban mobility - which are all better described in the following item.

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<sup>2</sup> <https://morahabitacao.com/digital-poe-1/>

### ***Elaboration of questions and feedback for the POE***

With the environmental quality of housing evaluation attributes defined, the questionnaires created were revised in view of the previous questionnaires, mentioned above, with the intention of: improving the existing questions, contemplating different typologies of housing and adding question to better verify the habits of the residents in terms of the reduction of environmental impacts of living. Therefore, tables of possible questions, relating to the attributes of the evaluation, were created.

Table 1. Attributes and aspects evaluated.

Evaluation attributes	Evaluated aspects
<b>Environmental comfort</b>	Natural ventilation Natural lighting Temperature Noise levels
<b>Water</b>	Reasons for saving water (or not) Actions to save water Water saving devices
<b>Electricity</b>	Reasons for saving electricity (or not) Actions to save electricity Solar energy equipment and systems
<b>Waste</b>	Recyclable materials x non-recyclable Collection points of recyclable materials Collection and disposal of: oil / waste of construction / batteries and electronic equipment / expired medicines
<b>Organic food</b>	Organic food consumption Reasons for consuming organic food (or not)
<b>Vegetation</b>	Presence of green areas in the house Reasons for cultivating plants (or not)
<b>Urban mobility</b>	Transport mode used according to distance Reasons for using specific kind of transport mode

In the questionnaire, the evaluation of environmental comfort of the units occurs through the identification of the level of satisfaction of respondents in reference to each room of the housing (physical scale) in terms of: natural ventilation, natural lighting, temperature and noise levels (Table 1). On the elaboration of the database, questions will be cross-referenced with other technical and constructional aspects evaluated (like, for example, the carrying out of refurbishments and improvements aiming at better living conditions and comfort in the rooms).

On the other hand, the block of questions aiming at identifying the level of environmental awareness of the residents divides their habits and actions in terms of: water and energy saving; reasoning for the saving of water and energy; the presence of solar energy (heaters and/or photovoltaic panels); use of water saving devices; the collection and disposal of waste (domestic, recyclable, oil, expired medicines, construction, batteries and electronic equipment); knowledge on collection points; consumption of organic food and justification; interaction with vegetation (presence of green areas on the plots and in the units as well as justification for their presence or absence) and urban mobility (common mode of transport and justification for its use).

With this in mind, the scales of evaluation were merged with one another, together with the general research, since the habits and actions (behavioural scale) relate to the residential unit itself (physical scale) revolves around the city in which unit is inserted (urban scale). To simplify the process of the elaboration of the proposed evaluation system, the

types of responses were also indicated: dichotomic (yes/no), trichotomic (yes/no/don't know), and multiple choice (possibility of more than one answer) and with on a semantic differential scale (on a scale of values). In the last case, a scale of values of 5 points was used to verify the perception of the user (resident) for that attribute under analysis. Moreover, the graphic resources (icons) to be used were indicated to support the team responsible for the design of the interface, as well as how the diversions should be created by the IT team.

Finally, feedback was proposed for the users, aiming to clarify any doubts on the questioned habits, or even triggering changes in the respondents' attitudes along their participation in the evaluation process (Table 2).

Table 2. Example of educational feedback related to the attribute "urban mobility".

<b>FEEDBACK – EVALUATION ATTRIBUTE: "URBAN MOBILITY" – QUESTION "R"</b>
<i>R) What transport mode do you most use in general?</i>
<ul style="list-style-type: none"> <li>- On foot</li> <li>- Bike</li> <li>- Car or motorcycle (FEEDBACK 17, if the interviewer answers this option)</li> <li>- Public transport</li> </ul>
FEEDBACK 17: According to several scientists, the emission of gases by private vehicles is a significant cause of global warming. Some strategies can be used to reduce these impacts, such as: creating a network of shared rides to go to work/school; using public transport at least once a week (since this mean of transport carries lots of people, it pollutes less than individual vehicles); and walking or cycling more frequently to places close to home (in this way, it is also possible to reduce air pollution and to improve physical fitness).

### ***Evaluation system for the quality of habitation over digital media***

The proposed evaluation system was structured in a way that relates to different attributes, investigated on a clear, intuitive path for the user, reinforcing the user-friendly qualities of the interface and exploring diversion resources which only digital media can offer (Cunningham, Zichermann, 2011; Villa et al., 2016). Therefore, the evaluation was organized - from the functional, behavioural and environmental aspects - into stages which begin with personal details and ending with the evaluation of the housing, divided into system tabs: about you; previous house; current house; condominium; housing unit; sustainable habits (Figure 1). The first tabs contain general data about the resident and housing (current and previous), while from the tab "surroundings" on, the questions evaluate the residential unit and the surroundings in which it finds itself. Thus, apart from the evaluation of environmental comfort of the unit, an exclusive block of questions on the actions of the residents was created in relation to sustainability.

The software for the evaluation system was programmed using the language JAVA while the database uses JAVA/NoSQL technology and the application for tablets and smartphones runs on the programming platform for games, CORONA SDK. The design of the interface sought: (i) to maximize the concentration of possible keywords on a single screen, relative to the attribute being assessed (aiming to optimize time spent to respond to the questionnaire); (ii) to use symbols, colors and animated images to represent these keywords; (iii) to facilitate multimedia resources for the animations; and (iv) to make varying data and information readily available for each attribute to be assessed.

With this in mind, specifically icons were created to better clarify the attributes in the evaluation, relative to the impacts that living has on the environment (Figure 2). In turn, the use of multimedia resources can be exemplified in the evaluation of environmental comfort of the units: for example, indicating temperature, using a thermometer; and using an icon of the sun to evaluate natural lighting. In return, information was made available to

users through the use of feedback. Furthermore, with the objective of making this evaluation system more interactive, a character was created, called "Dr. Clipboard" that aims to accompany the respondent through, practically, the whole assessment, appearing in different forms on the screen. The chromatic palette adopted was used to aid the proposed structure of the questionnaire: the tab "sustainable habits", for example, being coloured in green, generally seen as representative of the idea of sustainability.

Finally, a first test of the developed system was applied in February of this year aiming to verify its viability and using a sample from 50 answered questionnaires. This application received a welcoming reception of the tool and demonstrated the necessity of some minor adjustments. The results are not the focus of this article.

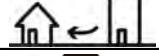
	<b>1. INTERVIEWEE PROFILE</b>	AGE, GENDER, EDUCATIONAL LEVEL, INCOME, DOMESTIC EMPLOYEES, FAMILY MEMBERS
	<b>2. PREVIOUS HOUSE</b>	CHARACTERISTICS OF PREVIOUS HOUSE LEVEL OF SATISFACTION WITH PREVIOUS HOUSE
	<b>3. SURROUNDINGS OF CURRENT HOUSE</b>	LOCATION OF CURRENT HOUSE LEVEL OF SATISFACTION WITH SURROUNDINGS (PUBLIC FACILITIES AND SPACES)
  	<b>4. CURRENT HOUSE</b>	CHARACTERISTICS OF CONDOMINIUM (COLLECTIVE FACILITIES AND SPACES)  EVALUATION OF THE HOUSE AS A WHOLE  EVALUATING OF ROOMS AND SPACES IN A SPECIFIC WAY DEFINITION OF THEIR USES (WAY OF LIVE)
	<b>5. RELATIONSHIP WITH THE ENVIRONMENT</b>	EVALUATING THE RESIDENT'S BEHAVIOR CONCERNING THE ENVIRONMENT AND ITS IMPACT
		

Figure 1. Tabs of the research and aspects evaluated.

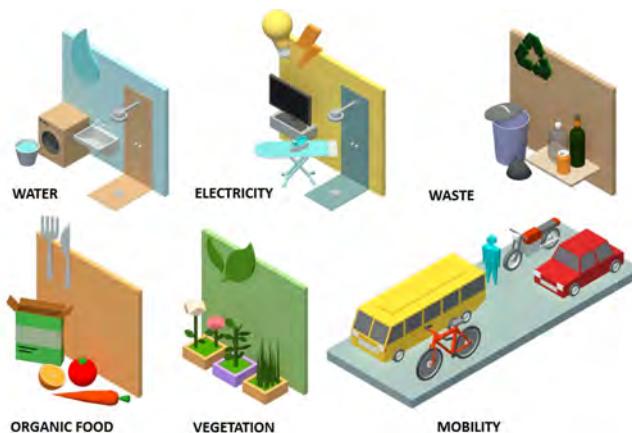


Figure 2. Icons related to sustainable habits.

## Conclusions

The interactive system for Post-Occupancy Evaluation of housing quality has the capacity to provide feedback into future projects, focusing on different scales of analysis (house product, behavioural relation of users and their residencies, and the insertion of habitation in urban surroundings). The open platforms of digital evaluation tools improves technologically in the sense that it brings the user (and their perceptions) closer to the constructed environment (and its attributed meanings) in a more interactive manner. It is

expected that it will be possible to precisely identify the expectations and anxieties of residents - especially in terms of environmental quality of the housing and the level of awareness residents have regarding the impacts of their actions.

Moreover, the establishment of databases on living, based on the statistical and scientific information collected, can amplify the environmental quality of projects in the area. The database is also configured as a means of communication between residents and the productive agents of habitation (public and private), as well as making the evaluation system, developed here, an instrument of information and knowledge for the users themselves on the different aspects related to living, including sociocultural dimensions, as much as of sustainability.

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## References

- Amore, C. S.; Shimbo, L. Z.; Rufino, M. B. (Org.). (2015). *Avaliação do Programa Minha Casa Minha Vida em seis estados brasileiros*. Rio de Janeiro: Letra Capital.
- Araújo, M. S. C. (2005). *Os donos da casa: das políticas de habitação aos significados da moradia*. Master. Universidade Estadual do Ceará.
- Cunningham, C.; Zichermann. (2011). *Gamification by Design: implementing game mechanics in web and mobile apps*. Sebastopol: O'Reilly.
- Kowaltowski, D. C. C. K; Moreira, D. de C.; Petreche, J. R. D.; Fabrício, M. M. (Org.) (2011). *O Processo de projeto em arquitetura: da teoria à tecnologia*. São Paulo: Oficina de Textos; FAPESP.
- Kunze, N.C.; Concianni, W. (2004). *Ensino, pesquisa e extensão: uma relação possível a favor da moradia*. Brasília: Secretaria de Educação Profissional e Tecnológica.
- Mallory-Hill, S.; Preiser, W.; Watson, C. (2012). *Enhancing Building Performance*. London: Wiley-Blackwell Press.
- Martincigh, L.; Bianchi, F.; Guida, M.; Perruci, G. (2016). The occupants' perspective as catalyst for less energy intensive buildings. *Energy and Buildings*, n.115, p.94–101.
- Penzim, A. M. B. (2007). Habitação social e modos de vida: narrativas sobre a casa e o morar. In: *Conference For Young Urban Researchers*, Lisboa, 11-12 July 2007. Lisboa: CIES.
- Stevenson, F. (2013). Avaliação de um ambiente planejado e a busca pela sustentabilidade ambiental em moradias. O caso do Reino Unido. In: Villa, S. B.; Ornstein, S. W. (Org.). (2013). *Qualidade ambiental na habitação: avaliação pós-ocupação*. São Paulo: Oficina de Textos. p.359-379.
- Villa, S. B.; Lemos, S. M.; Salustiano, L. R.; Ribeiro, G. P. N. (2016). Inovação tecnológica na avaliação pós-ocupação: ferramentas digitais e interativas. In: *Encontro Nacional de Tecnologia do Ambiente Construído*, São Paulo, Brazil, 21 - 22 September 2016. São Paulo: ANTAC.
- Villa, S. B.; Ornstein, S. W. (Org.). (2013). *Qualidade ambiental na habitação*. São Paulo: Oficina de Textos.
- Villa, S. B.; Saramago, R. C. P; Garcia, L. C. (2015). *Avaliação pós-ocupação no programa Minha Casa Minha Vida: uma experiência metodológica*. Uberlândia: Universidade Federal de Uberlândia; PROEX.
- Visscher, H.; Werf, E. V.; Voordt, T. J. M. V. (2013). Eficiência energética no parque habitacional holandês. In: Villa, S. B.; Ornstein, S. W. (Org.). (2013). *Qualidade ambiental na habitação: avaliação pós-ocupação*. São Paulo: Oficina de Textos. p.343-358.
- Voordt, T. J. M. V.; Wegen, H. B.R. (2013). *Arquitetura sob o olhar do usuário. Programa de necessidades, projeto e avaliação de edificações*. São Paulo: Oficina de Textos.
- Yudelson, J. (2016). *Reinventing green buildings: why certification systems aren't working and what we can do about it*. Gabriola Island: New Society Publishers.



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*Design to Thrive*

## Building façade design for indoor air temperature and cooling load reduction

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**Abstract:** In the tropical country of Singapore, building envelope accounts for a substantial portion of cooling load in buildings. In order to reduce the air-conditioning load and maintain indoor thermal comfort, this work is dedicated to study the thermal performance of building façade of residential block in Singapore. Residential units located at the same height but with different design features are selected, so as to study the impact of corridor shading, window-to-wall ratio and internal shading on the indoor environment. Field experiment is carried out to measure the indoor air temperature, relative humidity, globe temperature and wall surface temperature for continuous days. The total and sensible cooling energy loads of these units are simulated using EnergyPlus program. The impact of building façade design and orientation on cooling load are thus estimated. Based on the analysis, recommendations are provided for the energy efficiency in residential buildings in tropics.

**Keywords:** residential buildings, window-to-wall ratio, passive design, energy simulation.

### Introduction

In the tropical country of Singapore, climate is hot and humid throughout the year. Air-conditioner is the largest contributor of energy use in both commercial and residential buildings. With 100% of its population urbanized, the city-state places major concern on the indoor thermal comfort as well as the space cooling energy savings. The building envelope separating the indoor space from the outdoor environment plays an important role, as it acts as a modifier of the direct effects of climate variables such as the outdoor temperature, humidity, wind, solar radiation and rain. Building envelope accounts for approximately 64% of the total cooling load in Singapore (Chua & Chou, 2010).

During the past few decades, tremendous research efforts have been spent on the passive design of building envelope for cooling energy savings in Singapore. Field experiments have been carried out to investigate the potential benefits of different passive envelope designs, such as rooftop garden (Wong, Tan, & Chen, 2007), solar-reflective roof (Tong et al., 2014), secondary roof (Wong & Li, 2007) and shading device (Wong, Tan, Seng, Mok, & Goh). In addition, simulation studies were conducted to analyse the impact of building façade design parameters as well, such as thermal insulation, induced natural ventilation flow, window-to-wall ratio and shading devices (Wang, Wong, & Li, 2007).

Some passive design features are commonly adopted by architects for energy efficiency in tropical climate, such as north-south orientation of windows, extended

canopies to provide sun-shading and casement windows to promote natural ventilation. However, in recent years, some high-rise residential buildings that cater to higher-income residents pay less emphasis on promoting natural ventilation and passive design strategies. For example, implementation of a full height glass façade is common, as they are deemed to provide better views and a luxurious appearance. This trend greatly increases the cooling load in residential buildings during daytime.

The Building Construction Authority (BCA) of Singapore has implemented regulations to control the heat gain into interior spaces and air-conditioning load (BCA, 2008). Several design parameters are considered to reduce the heat gain of building envelope, including window-to-wall ratio (WWR), shading coefficient, U-value of wall and external shading device.

In this study, field experiment is carried out to investigate the impact of corridor shading, window-to-wall ratio and indoor shading blind on the indoor air temperature, globe temperature and thermal comfort. Furthermore, energy analysis is performed to study the impact of WWR, shading device and building orientation on the sensible and total cooling loads.

## Field measurement

### *Experiment set-up*

Field experiment is carried out on a public residential block on East Coast road in Singapore. As shown in Figure 1 (a), the 5-story residential block was designed as a slab block and built in 1970's. There are 7 residential apartments on each floor, and each apartment consists of 1 living room, 1 kitchen and 1 bedroom. As shown in Figure 1 (b), the studied facade is west-east orientated facing a car park. The residential block was evacuated during our experiment period in December of 2016.



Figure 1. (a) Studied residential block and (2) map of its surroundings.

Five west-facing units located on the fourth floor of studied block are selected for experiment, as shown in Figure 2 (a)-(e). As illustrated in Figure 2 (f), a 1.3-m wide corridor is designed as common area outside the units A, D and E, while selected façades in unit B and C are exposed to outdoor environment without corridor shading. The WWR of these west-facing facades of units A-E are 0.2, 0.5, 1, 1 and 1 respectively. Inside the units, no internal shading device is used in units A-D, while a white blind is used in unit E to block the incoming solar heat.

In each selected unit, air temperature, relative humidity and globe temperature at 1.1-m or 0.6-m height, 30-cm distance from interior surface of west-facing facade are measured.

Moreover, the surface temperatures of exterior and interior façade surfaces are measured continuously. Air temperatures and relative humidity are measured using HOBO temp/RH data logger (Model U12-011). Globe temperature is measured using HOBO thermocouple data logger and customised globe thermometers (Tan, Wong, & Jusuf, 2013). All the measurements are conducted with the windows of these units being fully closed, and the measured data is collected at 1-minute interval.

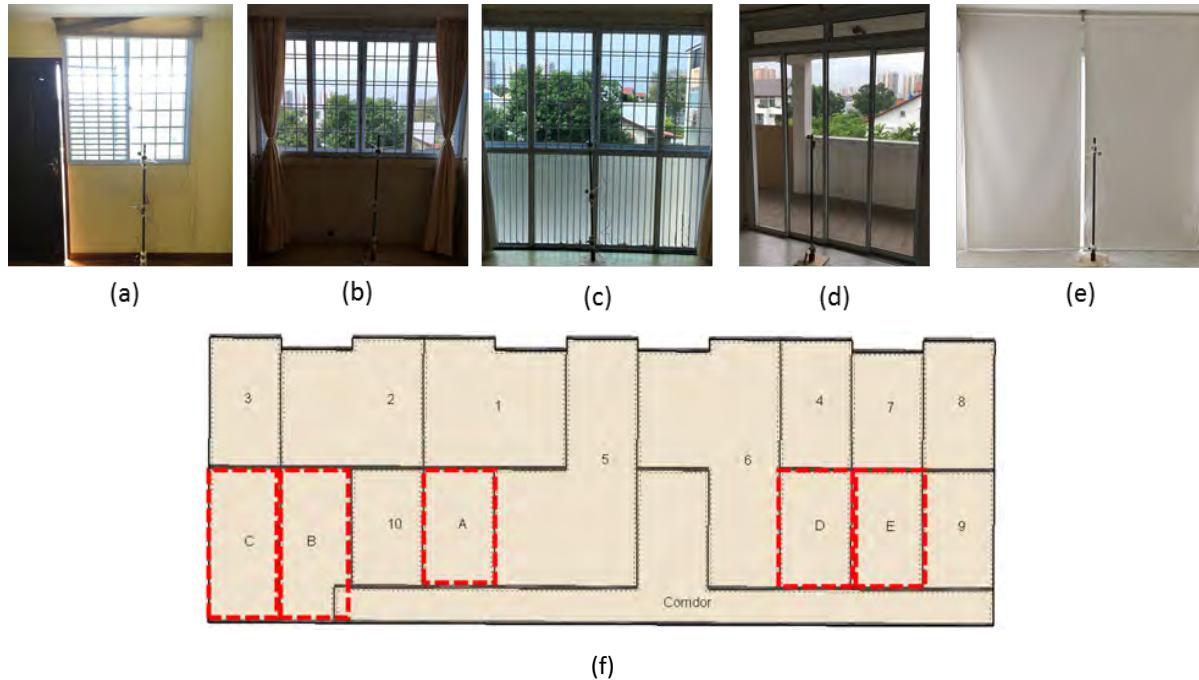


Figure 2 (a)-(e) Studied façades in Units A-E and (f) floor plan for 4<sup>th</sup> story.

### **Experimental data analysis**

In order to compare the thermal performance of selected facades on sunny days, weather data at a nearby meteorological station is collected. As shown in Figure 3, the hourly solar radiation intensity and air temperature on a sunny day (Dec 14, 2016) are illustrated. It is observed that solar irradiation reaches its peak at  $852 \text{ W/m}^2$  at 1 p.m., and the peak air temperature is  $33.3^\circ\text{C}$  at 4 p.m. The walls are made of 15-cm thick reinforced concrete. All the windows are made of clear glasses, except for the clear glass with frosted film at the lower part of Unit C's windows for privacy.

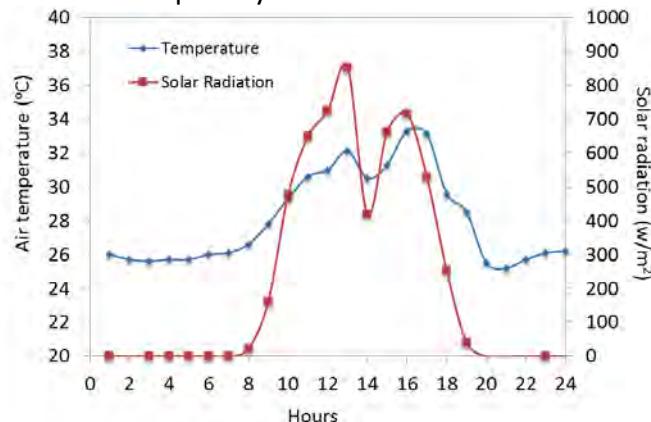


Figure 3. Hourly temperature and solar radiation on the measurement day.

### *Impact of external corridor shading*

The impact of corridor shading on the indoor temperature is studied by comparing the thermal environment in Unit C and D. Both facades use full height glass windows, and there is a 1.3-wide corridor outside unit C. The hourly variations of air temperature and globe temperature in Unit C and D are presented in Figure 4. In both units, air temperature peaks at 6 p.m. when solar radiation penetrates the windows and transmits indoors. Moreover, air temperature in Unit D is 7.6°C lower than that in Unit C at 5 p.m. due to corridor shading. On average, the shading provided by 1.3-m corridor helps to reduce indoor air temperature by 3.6°C from noon to 9 p.m., and the reduction is 2.0°C over 24 hours. The reduction in globe temperature due to corridor shading is also evident, which reaches its maximum at 6.7°C at 5 p.m. The globe temperature reduction due to corridor shading is more than 1°C from 2 p.m. to 7 p.m., when direct sunlight hits the studied façade.

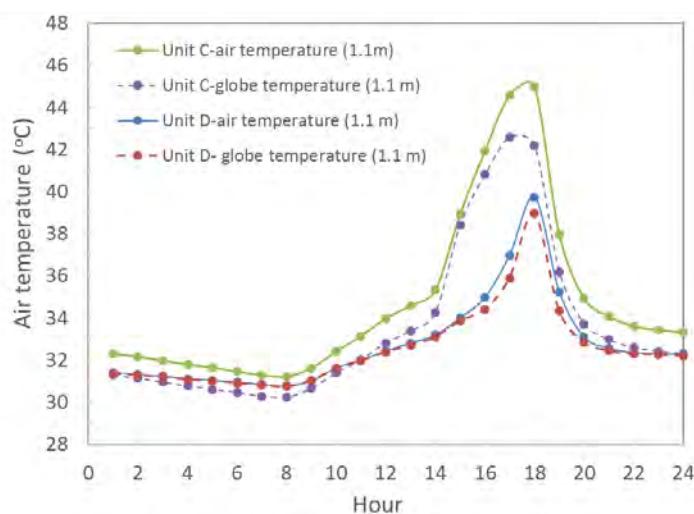


Figure 4. Comparison of temperatures between units C and D.

### *Impact of window-to-wall ratio*

The impact of WWR on indoor thermal environment is investigated by comparing the air temperatures in units A and D, as well as those in units B and C.

As shown in Figure 5, the hourly variations of air temperature and globe temperature in Unit D at 1.1-m height, in unit A at both 0.6-m and 1.1-m are compared and analysed. The WWR of units A and D are 0.2 and 1 respectively, and both units are shaded by corridor. In the afternoon, air temperature is reduced from 39.7°C in Unit D to 37.8°C in Unit A at 1.1-m height due to the smaller WWR in Unit A. Moreover, the peak air temperature at 0.6-m is 3.3°C lower than that at 1.1-m in Unit A, which indicates that the indoor space with direct sunlight is significantly hotter than the shaded area. Moreover, in the afternoon, the difference in globe temperature between Unit D and A is more significant than that in air temperature at 1.1-m height, reaching 6.3°C at 6 p.m. It indicates that large WWR is a main contributor to the thermal comfort problem in Unit D during the daytime. However, the situation is reversed at night, when the air temperature in unit A becomes slightly higher than that in Unit D with full height window, due to better thermal insulation of unit A.

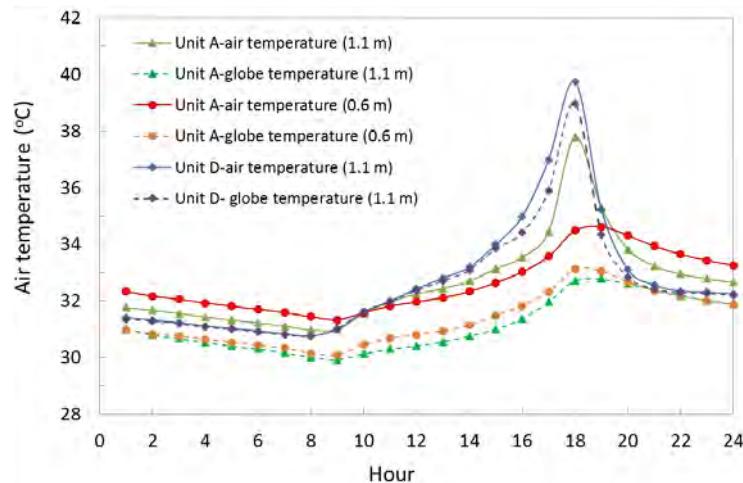


Figure 5. Comparison of temperatures between units A and D.

As shown in Figure 6, hourly variations of temperature at the measurement points in units B and C are presented. Units B and C are not shaded by corridor, and their WWR are 0.5 and 1 respectively. In the afternoon, the peak air temperatures reach 45.0°C, 43.0°C and 36.4°C, at measurement points in unit C at 1.1 m, in unit B at 1.1 m and 0.6 m respectively. At 1.1-m height, the measurement point in unit B is on average 2°C cooler than that in unit C from noon to 6 p.m., due to smaller WWR and better thermal insulation in unit B. In unit B, the temperature difference between measurement points at 1.1 m and 0.6 m is also evident, reaching 6.3°C for air temperature and 5.3°C for globe temperature respectively. It is thus concluded that the direct sunshine from the west-facing window in the afternoon is the main contributor to temperature rise in the studied units.

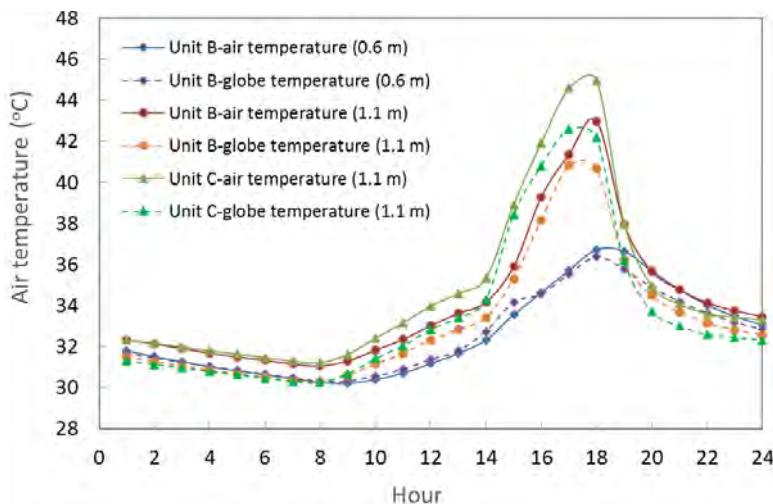


Figure 6. Comparison of temperatures between units B and C.

#### *Impact of internal shading blind*

As shown in Figure 7, the hourly variation of air temperatures in units D and E are compared. Both units are equipped with full-height windows, and a white blind is used in Unit E. It is found that the internal shading blind helps to reduce the peak air temperature and globe temperature by 2.1°C and 2.7°C respectively. The cooling effect of blind might be more effective if the units are not shaded by corridor. At night, the impact of internal shading blind on indoor temperature becomes negligible.

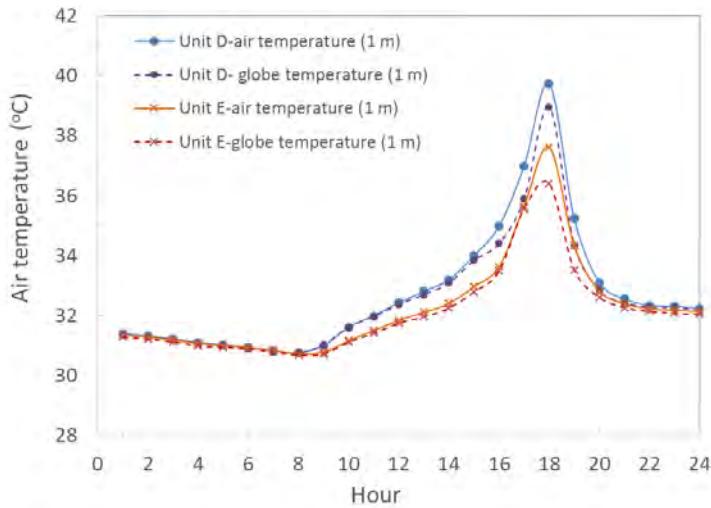


Figure 7. Comparison of temperatures between units D and E.

It is noticed that the indoor air temperature insides all the studied units are very high in the afternoon. The peak temperatures at 1.1-m range from 45.0°C in unit C to 37.8°C in unit A, when the outdoor air temperature is only 33.3°C. It might because that the windows of studied units are all closed, and heat built up in a glass window environment. When half of the windows on the studied facade are opened, the indoor temperature rise becomes less significant. For example, on a sunny day (Dec 26 2016), the hourly variations of outdoor conditions and indoor air temperatures are depicted in Figure 8. It is observed that the peak air temperature in unit A is 33.3°C, which is 2.4°C higher than the outdoor air temperature at 4 p.m.

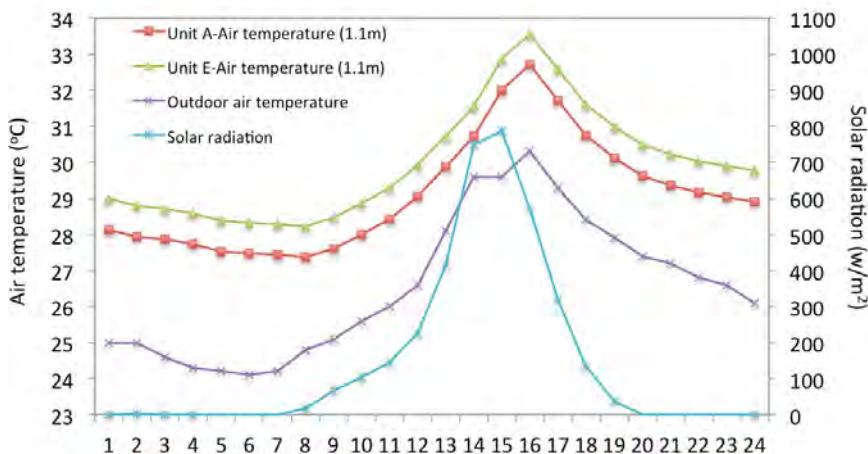


Figure 8 Hourly variations of indoor air temperatures under windows half-open conditions

### Computer simulation of cooling load

In order to investigate the impact of building façade design on cooling load, the total and sensible cooling loads of units A-E are simulated using Energyplus. The studied building facade is made of 10-cm reinforced concrete walls and clear glass windows.

As shown in Figure 9, a 3-D model of the studied block is built up in DesignBuilder, and the impact of neighboring buildings on the cooling load is thus considered. The sensible and latent cooling loads in units A-E on the hot day of July 15 are simulated, when the indoor air temperature is kept at 25°C. As illustrated in Figure 10, the sensible cooling load consists of 68%-83% of total cooling load among the 5 units. Unit C with full-height glass window and

without corridor shading shows the largest sensible cooling load of 3.86 kW per day. Unit B has the second largest sensible cooling load of 2.38 kW, followed by unit D, E and A. Unit A with corridor shading and smallest WWR has the lowest cooling load. It is also observed that the sensible cooling loads in units A and E are quite close, although they have different WWR. It might because that, although Unit E with larger WWR has more solar gain during daytime, windows also facilitate heat dissipation at night.

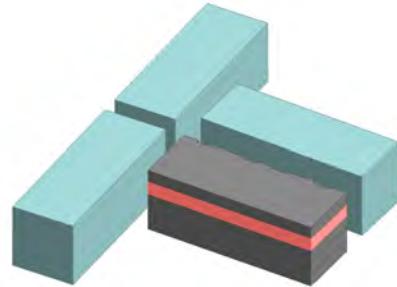


Figure 9. Building model in DesignBuilder.

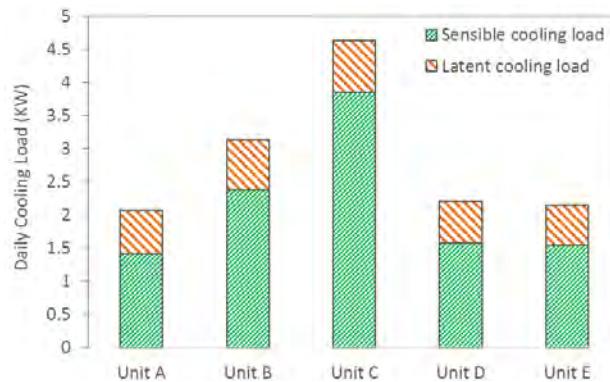


Figure 10. Total and sensible cooling loads of studied units.

The impact of building orientation on cooling load is also studied. The monthly sensible cooling loads of unit B under different orientation scenarios are simulated, as shown in Figure 11. From May to Aug when direct solar radiation reaches the northern hemisphere, the cooling loads of Unit B with west, east and north orientation are quite close, which are much higher than that with south orientation. In contrast, the cooling load of unit B with north orientation is the lowest from Nov to Feb. It is observed that the normalized sensible cooling load of Unit B per year is the largest at 159.4 KWh/m<sup>2</sup> for west orientation, followed by the east, north and south orientations of 152.0 KWh/m<sup>2</sup>, 139.5 KWh/m<sup>2</sup> and 138.5 KWh/m<sup>2</sup> respectively.

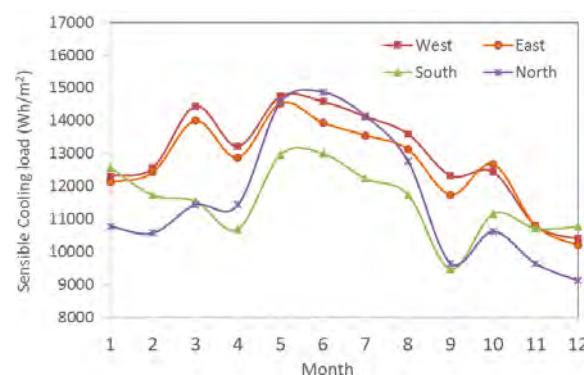


Figure 11. Sensible cooling load of Unit B under different orientations.

## **Conclusions**

In this work, the impact of WWR, external shading corridor and shading device on indoor temperature and cooling load are analysed through field experiment and simulation.

In field measurement, it is found that the corridor shading reduces the indoor air temperature by 7.6°C at 5 p.m. and by 2.0°C over the 24 hours for units with full-height glass windows. The reduction in globe temperature due to corridor shading is substantial and reaches 6.7°C at 5 p.m. For those units with corridor, the indoor air temperature and globe temperature at 1.1-m height are lowered by 1.9°C and 6.3°C respectively when the WWR of unit is reduced from 1 to 0.2. Moreover, the internal shading blind can reduce the peak air temperature by 2.1°C and reduce the peak globe temperature by 2.7°C in the afternoon.

Through computer simulation, the impact of façade design parameters on the cooling load of studied units are analysed. It is found that, compared with the worst-performing unit without corridor and with full-height glass, the sensible cooling load can be reduced by 38% through reducing the WWR to 0.5 and by 59% through corridor shading. The annual sensible cooling load of residential unit with west orientation is the largest, followed by those with east, north and south orientations.

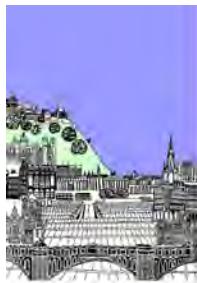
The results of this work can be utilized to improve the passive design of residential buildings so as to improve the indoor thermal comfort. Future studies will be conducted to study the comprehensive impact of different shading devices and advanced materials on the thermal performance of building façade.

## **Acknowledgement**

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## **References**

- Building Construction Authority, Singapore. Code on Envelope Thermal Performance for Buildings. (2008).
- Chua, K. J., et al, (2010). Energy performance of residential buildings in Singapore. *Energy*, 35(2), 667-678.
- Tan, C. L., et al, (2013). Outdoor mean radiant temperature estimation in the tropical urban environment. *Building and Environment*, 64, 118-129.
- Tong, S., et al, (2014). Thermal performance of concrete-based roofs in tropical climate. *Energy and Buildings*, 76, 392-401.
- Wang, L., et al, (2007). Facade design optimization for naturally ventilated residential buildings in Singapore. *Energy and Buildings*, 39(8), 954-961.
- Wong, N. H., et al, (2007). A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore. *Building and Environment*, 42(3), 1395-1405.
- Wong, N. H., et al, Performance of Passive Design Features in Zero Energy Building of Singapore, International Conference on Sustainable Design and Construction, 2011.
- Wong, N. H., et al, (2007). Study of thermal performance of extensive rooftop greenery systems in the tropical climate. *Building and Environment*, 42(1), 25-54.



# PLEA 2017 EDINBURGH

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## Retrofit for Optimizing Building Thermal Performance in Warm-Humid Climate

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**Abstract:** In existing educational buildings, spatial layout over time is altered to meet functional requirements. However, these can adversely affect the thermal comfort of occupants. Spatial and structural retrofit can improve thermal performance of buildings. This research puts forth the results of a real-life retrofit project to improve building envelope and interiors for better thermal performance of an existing educational space in warm and humid climate of Mumbai. The aim of the research is to analyze the effect of retrofit measures on building thermal performance. Measurements of air temperature, relative humidity and surface temperature of the sloping roof—the largest exposed envelope surface - were undertaken pre and post-retrofit using appropriate instrumentation. Key factors analyzed include change in roof under-deck surface temperature, surface area to volume ratio, change in U-factor and Envelope Performance Factor of building elements pre and post-retrofit. Results show a significant drop in internal surface temperature of the roof post retrofit, which has a positive effect on the MRT and subsequently the operative temperature and thermal comfort of occupants. The retrofit measures used are economical and have potential for scaling-up across educational buildings in India, where low-cost solutions for thermal comfort and energy efficiency, are much required.

**Keywords:** thermal performance, retrofit, roof, envelope performance factor, warm humid climate, educational building

### Introduction

As per the Central Regulatory Authority (CEA) 2013 Report, building sector in India accounts for 37% of total electricity consumption. Energy consumption due to space cooling and lighting has been found to account for one third of total energy consumption in residential buildings and two-thirds of total energy consumption in commercial buildings in India (Bhatt, Rajkumar, Jothibasu, Sudirkumar, Pandian, & Nair, 2005).

The building envelope acts as a mediator between the external environment and the occupants. It forms a significant element in total energy consumption and has a cascading effect on air conditioning and lighting. Hence, designing the building envelope for improved thermal performance is important for occupant comfort and energy consumption. Retrofit of existing buildings for energy efficiency can be costly and limited.

### ***Retrofit Strategies for Improved Thermal Performance in Warm Humid Climate***

Warm-humid climates pose a peculiar problem for thermal comfort of human beings. While the air temperature may be in the early 30s of degree Celsius, the high relative

humidity results in great thermal discomfort. Retrofit strategies for warm-humid climate predominantly require increased air movement and reduced exposures to solar heat (Olgay, 1963).

### ***Indicators of Thermal Performance***

**Mean Radiant Temperature (MRT)** is an important indicator of thermal comfort and performance. It is a measure of the average radiant temperature of surfaces within a space. It is suggested to maintain the MRT of a space below body/skin temperature ( $37^{\circ}\text{C}$  or  $98.4^{\circ}\text{F}$ ) to avoid net inflow of heat of the occupant's body through radiation heat transfer (Sehgal, 2010).

**Surface temperature** of walls and roofs are important indicators as they affect MRT and in turn the Operative temperature and thermal comfort. In this project, the roof area was 66.4% of total envelope area (excluding floor being on the sixth floor) and hence surface temperature of roof was considered an important indicator of thermal performance.

**The Envelope Performance Factor (EPF)**, the trade-off value for the building envelope compliance option in ECBC 2007 has been used as an indicator as it considers the surface area of specific building envelope element, the U-factor or rate of heat transmission through the component, the Solar Heat Gain Component (SHGC) and a multiplier to account for shading of fenestrations.

### **Objective, scope and limitations**

The main objective of the paper is to analyze the effect of retrofit measures for an existing naturally ventilated daytime space in a college building for thermal performance in warm-humid climate of Mumbai.

The heat-gain reducing and heat-loss promoting strategies are based on existing principles described above but also governed by limitations of budget, limitations of building byelaws and client requirements. The effect of the strategies is analyzed with respect to building thermal performance with focus on roof (being the largest surface area exposed to solar radiation)

### **Methodology**

The study is located in the city of Mumbai, India, which is classified under warm-humid climate zone by the ECBC 2007. The research design is quantitative and includes measurements and calculations related to thermal performance of the building and its elements – pre and post-retrofit.

The retrofit project was undertaken in September 2012 and completed in March 2014. The project included retrofit design and layout, discussions with client (Director of the College) and users to meet their functional and spatial requirements and approval of budget, preparing tender documents, specifications and rate analysis for items not listed in the District Schedule of Rates (DSR).

Pre and post-retrofit analysis of design was based on calculations of surface-area to volume, U-value and EPF (Envelope Performance Factor), and measurements taken using Digital Hygro-thermometer, Electronic Infrared non-contact Thermometer, K-type (thermocouple) and RTD-PT-100 sensors and 8 channel data logger.

### **Analysis of existing building**

The space under consideration admeasures 6938 sq. ft. (643 sq. m) located on the sixth (top-most) floor of one of three wings of a college building in South Mumbai. A post-independence construction, the design has a distinctive art-deco style reflected in the rounded columns, balconies and timber framed windows and doors. While the college management intended to renovate and redesign the sixth floor to meet its changing educational and spatial requirements, it also intended the renovation to address the problem of thermal discomfort of occupants.

### **Analysis of existing building envelope**

The space is situated on top of 5 floors of the northern wing that is one of three rectangular blocks that comprise the C-shaped college campus building. The rectangular block is 33.3m in length and 19.2m wide. The longer axis is parallel to north and south. Both sides are flanked by a buffer space in the form of a long balcony corridor, which is 2.25m wide in the north shaded with a 0.6 m *chajja* and 1.65m *verandah* on the south fully shaded by a concrete shading device. The Window Wall Ratio (WWR) is 23.5 and 21.09% on south and north facades, and 14.79% on eastern façade. The western part of the block is connected to the rest of the building by a staircase and toilet block and passage.

The gable roof admeasuring 7296.639 sq. ft. (677.88 sq. m.) is made of asbestos cement sheets nailed to a steel truss that sits atop the brick walls along the building envelope. It includes translucent polycarbonate sheets provided for daylighting along the central corridor. The skylight-to-roof ratio (SRR) was 5.6% prior to retrofit.

It is a daytime use building as classes and offices close by 5pm. Proximity to Arabian Sea brings in cool winds from the northwest and west (prevailing and secondary wind direction for Mumbai). Peripheral walls are of brick masonry with cement plaster about 450 mm thick.

The existing building has ideal form (length to width ratio is 1:7) and orientation along east-west axis to reduce heat gain (Olgay, 1963). Further, windows are provided with horizontal shading on north and south to reduce solar heat gain in summer and optimize day-lighting. WWR is also below 25% on north and south and 14% on East. The building is oriented to face sea breeze from NW-W. However, doubly banked corridors with two layers of classrooms, blocked wind movement and reduced window openings.

### **Analysis of existing building interiors**

By way of volume, 19% of interior space prior to retrofit was enclosed within a false ceiling. A plywood false ceiling framework supported a Plaster of Paris (POP) false ceiling for all classroom and office spaces except the 18 m long central corridor.

The space comprised a mix of classrooms, offices, computer labs and HOD office separated by plywood partitions and 150 mm thick brick walls. The interior layout of classrooms rendered several windows un-openable. The spatial distribution of the space with two rooms placed one after the other between the external balcony corridor and the central inner corridor, provided little cross ventilation. Inner spaces were 'hot and suffocating' according to the occupants prior to retrofit.

### **Retrofit for improving thermal comfort – measures and materials**

The retrofit design of the space included reorganizing the space to meet the new functional requirements of the college. The functional requirements of the space required a layout

with classrooms for 80, 40 and 20 students respectively. Figures 1 - 3 provide a summary and photos of the retrofits on the 6th floor. Retrofit for thermal comfort was done by spatial and structural/ material measures which are summarized in Table 1.

### **Analysis of measurements and calculations pre and post-retrofit**

The measurements were taken pre-retrofit (September 2012), at various stages of dismantling and construction (May 2013 and December 2014) and post-retrofit (May and October 2015). The Envelope Performance Factor (EPF) was calculated pre and post retrofit based on the formula provided in Appendix E of the ECBC 2011 (Bureau of Energy Efficiency and USAID ECO III Project, 2009).

Table 1: Retrofit measures and their purpose

<b>Structural Retrofit</b>		
<b>S.No.</b>	<b>Strategy</b>	<b>Purpose</b>
1	100 mm thick dry wall internal partitions supported by Galvanized Iron (GI) channels, and vertical studs at 600 mm centre to centre clad with a double layer of gypsum plasterboard screwed and taped, and filled in with glass wool insulation material - in place of 150 mm brick walls and plywood partitions.	For better heat and sound insulation, and faster construction.
2	High albedo paint having solar reflective index > 0.5 on asbestos cement roof sheet .	For reducing cooling load of buildings
3	Radiant Barrier under-deck insulation made of polyethylene air bubble film (ABF) laminated with aluminum foil on both sides underneath the AC sheet roofing suspended using a G.I Wire mesh with an air gap of 100mm. The composite thickness of the material is 4mm; its emissivity is in the range of 0.01-0.04 and its thermal transmittance is 0.07W/m2K.transfer	To reduce emission of radiation from roof surface. This is a radiant heat reflective low-e insulation material meant to effectively block the
4	Rotating head Roto Turbo ventilators – 12 nos. – of throat diameter 300mm introduced on the roof to facilitate stack ventilation in the classrooms. Made of aluminum with steel shaft, they are fixed onto the AC sheet of the roof. At wind speed of 6 km/hr, it is projected to have an exhaust capacity of 572cfm.	To induce stack effect and provide thermal comfort to occupants by means of induced convective ventilation
5	Translucent uniform flat polycarbonate sheets fixed on Mild Steel (MS) cleats provided onto existing MS roof truss at 200mm centre-to-centre gas welded to match the level of dry wall. A thin layer or EPDM flat strips or rubber flats are pasted on to the cleats or the MS flat along its inner side using, rubber adhesives and cured to dry	They provide acoustic insulation while allowing daylight penetration into classrooms.
6	19 nos. 1.5mm thick 1.0 x 2.0 m (effective opening) corrugated translucent AC profiled polycarbonate sheets were fixed onto AC sheets to provide day-lighting. The sheets are placed in a similar form and orientation to a regular AC sheet and lapped on the top and bottom by 150mm.	To provide adequate daylight in the classrooms
<b>Spatial Retrofit</b>		
<b>S.No.</b>	<b>Strategy</b>	<b>Purpose</b>
7	Increase size of classrooms and provide single row of classrooms in place of double rows on either side of the corridor	To enhance thermal comfort through cross
8	Removal of false ceiling	To allow for stack
9	Increase WWR by making all windows openable	To enhance cross

## Results and Discussions

### *Effect of Solar Radiation on roof*

Roof-bottom temperature surface temperatures post-retrofit lie below 32°C (well below skin temperature) except along the ridge where the higher temperature can be attributed to the bitumen covered ridge sheet (Fig. 4).



Figure 1: Spatial layout before and after retrofit



Figure 2: Photo of Classrooms before and after retrofit

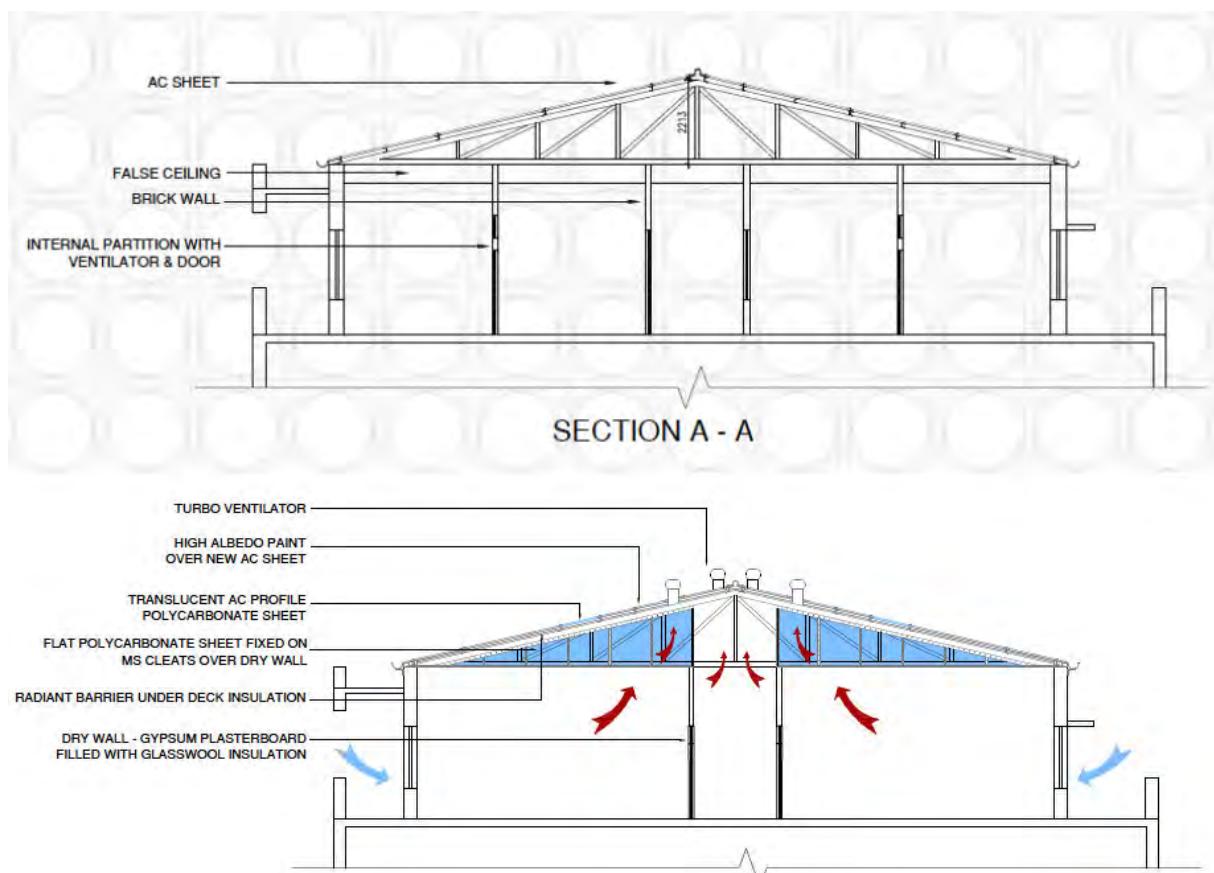


Figure 3: Pre and Post-retrofit section

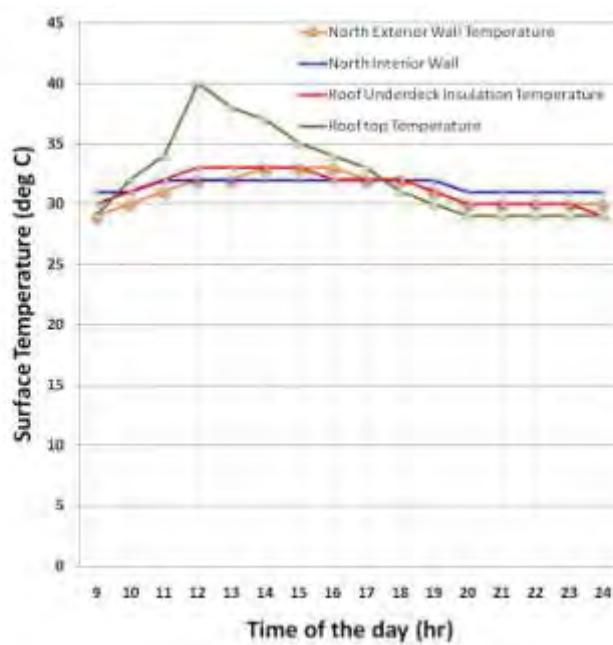


Figure 4: Roof bottom temperatures post retrofit are below 32°C

## **Analysis of retrofit measures based on calculations**

### ***Envelope Performance Factor***

The retrofit has major impact on roof U-value (a measure of thermal transmittance of a building element such as wall, roof or opening) which reduced from 4.64 W/m<sup>2</sup>K to 0.07 W/m<sup>2</sup>K due to the use of under-deck radiant barrier with a low emissivity of 0.04% and thermal resistance of 13.7K m<sup>2</sup>/W along with 100mm air gap. The low emissivity of the radiant barrier material, which is a major surface area in each classroom, means low MRT and hence enhanced comfort conditions for occupants (Sehgal, 2010). Calculated Envelope Performance Factor (EPF) of the retrofitted roof is reduced by 98% and of the retrofitted space by 94% (Table 2).

### ***Analysis of retrofit measures based on measurements of roof surface temperature:***

Based on ambient air temperature and humidity data collected from the Indian Meteorological Department (IMD) pre and post-retrofit, the surface temperatures of roof under-deck were compared. The post retrofit temperature for similar climate factor shows a difference of about 10°C (Fig. 5).

Table 2: Analysis of retrofit measures based on calculations

Building Component	Property of Material		As per ECBC
	Before RETROFIT	After RETROFIT	
Roof U-value	4.64 W/m <sup>2</sup> K	0.07 W/m <sup>2</sup> K	≤0.409 W/m <sup>2</sup> K
External Wall U-value	2.0 W/m <sup>2</sup> K	2.0 W/m <sup>2</sup> K	≤0.44 W/m <sup>2</sup> K
Window U-value	7.1 W/m <sup>2</sup> K	7.1 W/m <sup>2</sup> K	≤3.3 W/m <sup>2</sup> K
Roof SRR	5.6%	6.5%	≤5.0%
WWR (north)	24.98%	24.39%	≤60%(total)
WWR (south)	23.5%	23.17%	≤60%(total)
WWR (east)	14.79%	19.71%	≤60%(total)
SHGC (north)	0.72	0.72	≤0.25(total)
SHGC (south)	0.35	0.35	≤0.25(total)
SHGC (east)	0.82	0.82	≤0.25(total)

Note: No change in U-value of wall (2 W/m<sup>2</sup>K), window (7.1 W/m<sup>2</sup>K) and skylight (8.52 W/m<sup>2</sup>K); Doors and ventilators are considered in calculation for WWR (Window-Wall Ratio); SHGC is corrected to include effect of shading

## **Conclusions and Future Work**

In a developing nation such as India, where it is estimated that 66% of building stock is yet to be constructed, energy consumption due to space cooling and lighting has been found to account for two-thirds of total energy consumption in commercial buildings (Bhatt, Rajkumar, Jothibasu, Sudirkumar, Pandian, & Nair, 2005).

Educational buildings in India are, by and large, naturally ventilated and used during the daytime. Occupants mainly remain in a stationary position for periods of up to 45 minutes at a time either listening to lectures or performing some other activity such as drafting, drawing, laboratory experiments or even discussing. The study indicates that retrofit measures including roof insulation, and enhancement of stack and cross ventilation, can be achieved at a cost of less than Rs. 200/- per sq. ft. (GBP 2.5) with reduction in indoor surface temperature of roof of up to 100C in peak summer. Such cost-effective measures can be applied on a large scale in schools and college buildings to improve thermal comfort and reduce energy consumption.

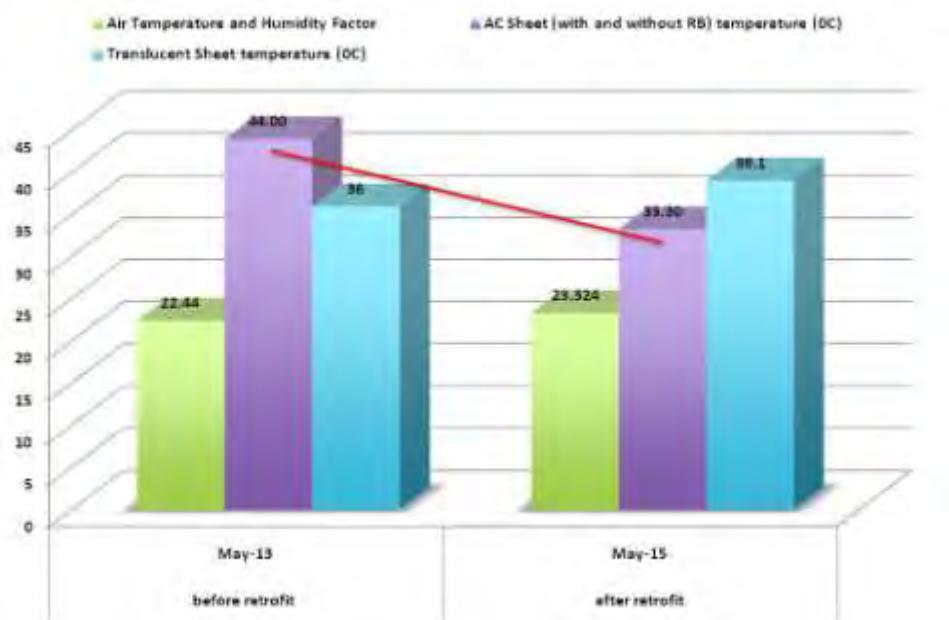


Figure 5: Analysis of retrofit measures – before and after retrofit shows nearly  $10^{\circ}\text{C}$  post-retrofit

## References

- ASHRAE. (1992). *Standard 55 - Thermal Environmental Conditions for Human Occupancy*. Atlanta: ASHRAE Inc.
- Bhatt, S., Rajkumar, N., Jothibasu, S., Sudirkumar, R., Pandian, G., & Nair, K. (2005). Commerical and Residential Building Energy Labeling. *Journal of Scientific and Industrial Research*, 30-34.
- Bureau of Energy Efficiency and USAID ECO III Project. (2009). *Energy Conservation Building Codes: User Guide*.
- (S. Kumar, Ed.) New Delhi, India: Bureau of Energy Efficiency.
- CSN ISO7726. (1993). *Thermal Environments: Instruments and methods for measuring physical quantities*. Prague: Czech Standards Institute.
- Hargas, L., Drkal, F., & Zmrhal, V. (2006). Experimental and Simulation Temperature Evaluation which Determine Thermal Comfort. *Journal of Mechanical Engineering*.
- Houghton, F., & Yaglou, C. (1924). *Cooling Effect on Human Beings Produced by Various Air Velocities*. American Society of Heating and Ventilation Engineers. Transactions.
- Fathy, H. (1986). *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot Arid Climates*. (W. Shearer, & A.-e.-r. A. Sultan, Eds.) Tokyo, Japan: United National University Press.
- ISO 7726:1998 (E). (1998). *Ergonomics of the thermal environment - instruments for measuring physical quantities*. Geneva: International Organization for Standardization.
- Kazkaz, M., & Pavelek, M. (2012). Operative Temperature and Globe Temperature. *Stekani Kateder Mechaniky Tekutin A Termomechaniky*, 26-28.
- Koenigsberger, O., Ingersoll, T., Mayhew, A., & Szokolay, S. (1973). *Manual of Tropical Housing and Building*. Hyderabad, India: Orient Longman Limited.
- Sehgal, N. (2010). Analysis of Structural Cooling System in Energy Plus. *International Conference on Current Trends in Technology, NUI CONE 2010*. Ahmedabad: Institute of Technology, Nirma University.
- Kumar, S., Kapoor, R., Deshmukh, A., Kamath, M., & Manu, S. (2010). *Total Commercial Floor Space Estimates*. New Delhi: Energy Conservation and Commercialization - ECO 3.
- Mahoney , C., Evans, J. M., & Koenigsberger, O. (1971). *Climate and House Design*. New York, United States of America: United Nations Department of Economic and Social Affairs.
- Nayak, J., & Prajapati, J. (2006). *Handbook on Energy Conscious Buildings*. New Delhi, India: Indian Institute of Technology, Bombay, and Solar Energy Centre, Ministry of Non-conventional Energy Sources, New Delhi.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Building Performance Evaluation for the Retrofit of Council Housing in the UK: A case study of a tower block in London**

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**Abstract:** The energy consumed in the domestic sector in the UK accounts for more than one fourth of the total CO<sub>2</sub> emissions in the country. Retrofit programmes aiming to improve energy efficiency of buildings have been initiated in the UK for more than two decades to achieve 80% reduction in greenhouse gas emissions by 2050. Building retrofit is a cost-effective way to reduce energy demand of existing buildings and improve thermal comfort. This research evaluates the building performance of a council tower block in London. Initial field surveys highlighted the serious damp and mould issues in several flats. This leads to health concerns caused by a combination of inefficient building envelope and partial unawareness of the occupants concerning efficient use of their homes. The research focuses on the interactions between the building performance, the occupants' energy consumption behaviour and thermal comfort in winter. In phase one of the project, building monitoring and simulation analysis were undertaken to assess the building performance and indoor thermal conditions. The second phase of the project focuses on the building performance optimisation and methods for energy efficient retrofit. This includes simulation analysis and a questionnaire-based survey to define the occupants' energy consumption behaviour and thermal comfort.

**Keywords:** Building performance, retrofit, council housing, simulation modelling, field monitoring

### **Introduction**

Improving the energy efficiency of the built environment is one of the major priorities of the UK government in order to reduce energy demand and deliver on the carbon emission reduction plan. The energy use in the housing sector in the UK accounts for more than twenty five percent of the total CO<sub>2</sub> emissions produced in the country (Low Carbon Innovation Coordination Group, 2012). The significant amount of carbon emission levels in the country show that there is a need to take initiatives to reduce the buildings' energy consumption and consequently mitigate the impact on climate change. Energy efficiency studies indicate that the suitable retrofit techniques can improve the building energy and environmental performance. Building retrofit also facilitates better indoor thermal comfort, health and wellbeing of the occupants while reducing the energy demands of the building (Vilches et al., 2017, Rickaby, 2011). However, the energy consumption of buildings is not always reduced by energy retrofit particularly in fuel poverty conditions (Vilches et al., 2017).

There have been major retrofit programmes rolled out by the UK government's Department of Energy and Climate Change (DECC) – now Department of Business, Energy and Industrial Strategy - to improve the energy efficiency of the buildings in the UK to achieve 80% reduction in CO<sub>2</sub> emissions by 2050 (Department of Energy and Climate Change, 2012). One major programme introduced is RENEW programme which aims to enhance the building

energy performance and reduce the impact of fuel poverty in London (Mayor of London, 2015). Studies show that in London Borough of Newham (LBN), there is high rate of fuel poverty at 13.8% (13,372 households) which is amongst the highest rates in the UK (Walker and Ballington, 2015b). Newham Council has been actively developing a plan to retrofit many of the existing domestic buildings particularly council housing. Improving the energy efficiency of the buildings in LBN, will cut the energy cost of the residential sector and reduce fuel poverty, while decreasing the carbon footprint of the properties (Walker and Ballington, 2015b, Walker and Ballington, 2015a). LBN's Council plan is to significantly reduce the number of fuel poor domestic buildings whilst achieving minimum energy efficiency standards of B and C by 2030 (Bromley-Dery, 2015). The Council also incorporates the UK national's best practice of the fuel poverty scheme in the borough's plan (Walker and Ballington, 2015b). However, there are some limitations in incorporating all the recommendations to the programme to improve the LBN's building energy efficiency. These limitations include low income levels of the households, high number of problematic private rented sector as well as health and age-related problems (Walker and Ballington, 2015a). Despite these barriers, Newham Council makes all the effort to increase the external funding for more support to the schemes.

The current study evaluates the building performance of a few of the typical problematic flats in one of the council tower blocks in LBN, planned for retrofit in the short term. This 22-storey tower block comprises of 108 properties; a combination of 1-bedroom and 2-bedrooms flats. The initial field surveys conducted by the LBN Community and Infrastructure team highlighted some major damp and mould issues within many flats (Medhurst and Turnham, 2016). The survey also confirmed water penetration issues in the tower block, which consequently resulted in poor indoor environmental conditions and concerns from the occupants about their comfort, health and wellbeing. The research focuses on the interactions between the building performance of the flats, the occupants' energy consumption behaviour and lifestyle, and the indoor thermal comfort in the winter months.

## **Methodology**

The aim of the study is to investigate the building performance of the 22-storey tower block in LBN with the purpose of reducing the building energy consumption and to improve indoor thermal performance by providing tailored recommendations for energy and cost-efficient retrofit. The study adopts a mixed method research design that includes field monitoring and a questionnaire-based survey. The project is being undertaken over two phases. The first phase of the project, the focus of this paper, is the building performance evaluation to identify and diagnose the possible causes of the physical issues of damp, mould and condensation. This process entails building simulation modelling and case study monitoring of indoor air temperature and Relative Humidity (RH) levels of a sample of flats in the case study identified as problematic to assess the building performance, the occupants' energy consumption behaviour and indoor thermal comfort. Flat A and Flat B have been selected as the exploratory sample case studied for the research, with a particular focus on the bedrooms. Both flats are located in the south-east orientation of the building in the middle floors of the block with similar damp, mould and condensation issues. Two zones were selected in each property to be monitored, the small bedroom representing a non-problematic bedroom and a master bedroom, which suffers from cold, mould and condensation. Building simulation modelling using dynamic DesignBuilder (DB) software was also performed to help understand and diagnose the issues with the building performance.

The second phase of the project focuses on the building performance optimisation and methods for energy efficient retrofit. This includes building simulation analysis and a questionnaire-based survey distributed to all flats of the block to understand the occupants' energy consumption behaviour and indoor thermal comfort and satisfaction. In this phase, the most sustainable and cost-effective practical recommendations for heating, cooling, and ventilation of the properties will be proposed. In addition, the most effective retrofit strategy will be recommended to improve the thermal envelope and to reduce the building overall energy consumption while providing a comfortable indoor environment. These recommendations can then be applicable to similar building types in the UK.

### ***Case Study: Tower block in London Borough of Newham***

The case under study is a council housing tower block located in London Borough of Newham. The 22-storey tower block was constructed in 1966 (Medhurst and Turnham, 2016) and consists of 108 2-bedroom and 1-bedroom properties. The structure is in-situ reinforced concrete frame construction with floor slabs spanning between shear walls and pre-cast concrete panels covering the flank wall. Externally, the building envelope is fitted with asbestos cement over-cladding panels. All flats have double-glazed windows with UPVC panels and internal wooden doors. The internal partitions consist of the concrete blocks of 100 mm thickness and the external walls include external over-cladding of 9 mm thickness, an 80 mm air gap, 200 mm pre-cast concrete panels and 20 mm internal wall insulation boards and finishes. Floors consist of 150 mm concrete slabs as well as floor and ceiling finishes. There is one extractor fan in the kitchen and another in the bathroom. The building heating is provided by natural gas fuelled hot water boilers.

From a survey undertaken by Newham Council in 2016 to diagnose the water penetration problems; it was found that 25 flats (23% of the tower block) experienced severe damp, mould and condensation issues (London Borough of Newham, 2016). In addition, an internal damp survey was carried out with the aid of a damp meter to identify the cause of damp penetration in the two sample flats (Figure 1) in the south-east corner of the tower under this study, flats A and B (Figure 2).



Figure 1. Damp and mould problems in Flat A (a, b, c) and Flat B (d, e) in the tower block in LBN

Based on the Newham survey results (Medhurst and Turnham, 2016), the building external over-cladding facades were jet washed in 2012 which may have damaged the sealing between the panels facilitating a path for water to penetrate the concrete structure during periods of driving rain. The second phase of this research will assess potential long-term solutions and will introduce the most cost-effective recommendations.

### ***Monitoring***

To evaluate the thermal and environmental performance of Flats A and B, the indoor air temperature and the Relative Humidity (RH) levels of the two main bedrooms of flats A and B (Figure 2) were monitored in the winter; from 25/11/2016 to 23/3/2017 using data loggers. Data loggers were fitted in each bedroom with the logging intervals of 15 minutes to collect indoor climatic data (air temperature and RH levels). They were located away from the heat

source and any direct solar radiation. Interviews with the occupants of the properties demonstrated they each have different lifestyles, various schedules for ventilation, heating, lighting and domestic hot water usage which have direct impact on the indoor air temperature and RH levels, as well as the energy consumption of the properties. In Flat A, the heating is turned on by a young family (2 adults and 3 children) from 8:00 pm until 7:00 am in both bedrooms whilst it is turned off in all other zones in the flat during a typical winter day. Both bedrooms are usually naturally ventilated for at least one hour every day. On the other hand, in Flat B, one elderly occupant keeps the heating off in both bedrooms whilst keeping the heating on from 8:00 am until 10:00 pm in all other zones of the flat and the occupant never opens any windows during the winter season for ventilation purpose. It should be noted that the master bedroom in both flats have apparent water ingress issues while the second bedrooms in both flats have no such issues. The on-site measurement results provides important data to identify and highlight issues regarding the thermal performance of the properties.

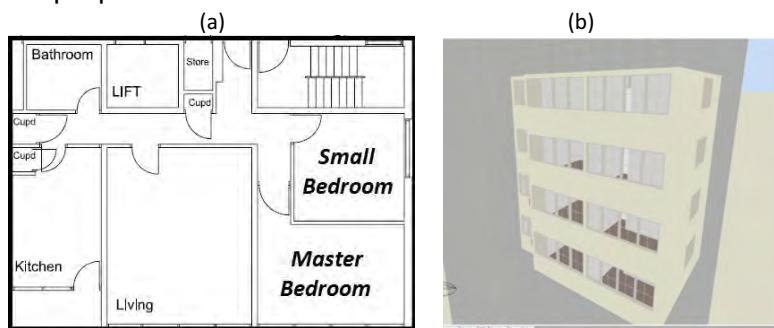


Figure 2. Floor plans of south-east flats (a) (London Borough of Newham, 2007) and the model on DB tool (b)

### **Building Simulation Modelling**

In addition to the on-site monitoring, the building performance of the two properties, Flat A and Flat B, was studied using the building simulation modelling, in this case DesignBuilder software (DB). Building performance of the two sample flats was assessed to provide more in depth understanding of the possible reasons for the mould and damp within the building fabric and the potential correlations with occupants' lifestyle and energy consumption behaviour. There has not been detailed information available about the building materials for the case study tower block in LBN. Therefore, the characteristics of the typical council housing tower blocks in London and in the UK, in the 1960s, were adopted to create a more accurate simulation model in DB. This will help to investigate the operational performance and enhance the energy consumption of the properties more accurately while improving the indoor thermal comfort. The most typical material used in this type of building in 1950s/1960s in the UK was pre-cast reinforced concrete panel designed for a life of at least 60 years (Malpass and Walmsley, 2005, Harrison and De Vekey, 1998, Colquhoun, 2008). Table 1 shows the U-values of the case study building components.

Table 1. U-values of the building envelope components of the case study tower block

Building Elements	Internal Partition	External Wall	Internal Floor	Glazing	Roof	Internal Doors
U-value W/m <sup>2</sup> K	2.93	0.78	1.82	2.67	0.28	2.82

To validate the building simulation analysis, the outdoor weather data obtained from the UK Meteorological Office (Met Office) for Gravesend weather station was incorporated into the simulation model's hourly weather file in DB, as well as the actual schedules for heating, ventilation, lighting and the domestic hot water usage in both flats. Later, the

software was validated and assessed against the field monitoring data from the flats that were modelled in DB. The measured indoor air temperature and RH levels in both flats were compared against the simulation results in DB. At this stage, the focus was on the coldest week of the winter season in 2016-2017 (17/1/2017 – 23/01/2017).

## Results and Discussion

The on-site monitoring results for the small bedroom and the master bedroom of flats A and B were gathered in order to assess the building performance and the environmental conditions as well as to analyse the damp and condensation issues. Figures 3 and 4 present the weekly mean indoor air temperature and RH levels of the measured rooms against the outdoor air temperature and RH. The results show that the indoor air temperature and RH levels in the measured bedrooms were usually within the acceptable comfort ranges in the winter. Generally, the RH range between 40% and 70% is acceptable for the sedentary occupancy while the indoor air temperature for the dwelling recommended to be between 17 °C and 19°C in bedrooms for winter conditions with clothing insulation of 1 clo and between 23 °C and 25°C for the summer conditions with clothing insulation of 0.5 clo (CIBSE, 2016). However, both flats have damp, mould and condensation issues in the master bedrooms, although the RH levels were usually in the acceptable range in the measured period. As discussed previously, the jet-washing of the building's external over-cladding facades might have damaged the sealing between the panels providing a path for water to penetrate the concrete structure where the impact might be magnified with the existing thermal bridges that can lead to internal condensation, damp and mould (Hopper, 2012).

Building simulation analysis were also performed on flats A and B during the coldest week of the winter season (17th-23rd January 2017) to represent the winter season for the simulation analysis. This is to assess the building performance and environmental conditions of the cases in more details (phase one) and to recommend the energy efficient retrofitting strategies which will result in reducing the dampness and the building's energy consumption (phase 2). Table 2 presents the mean, maximum and minimum climatic data measured with the data loggers during the coldest week of the measurement period.

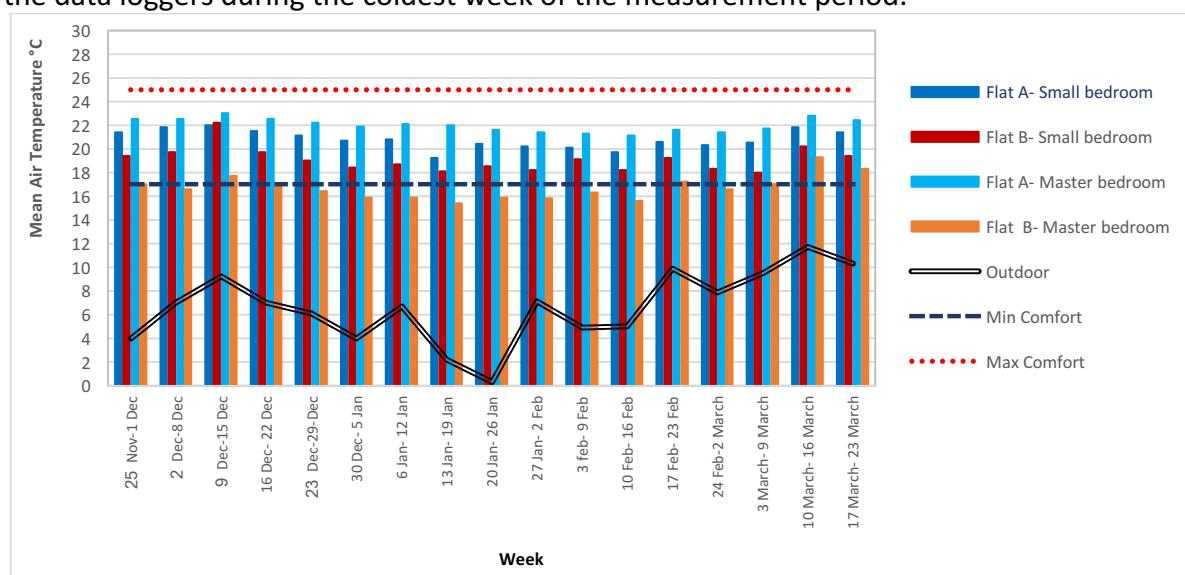


Figure 3. Weekly mean indoor air temperature against outdoor air temperature in small and master bedrooms in flats A & B

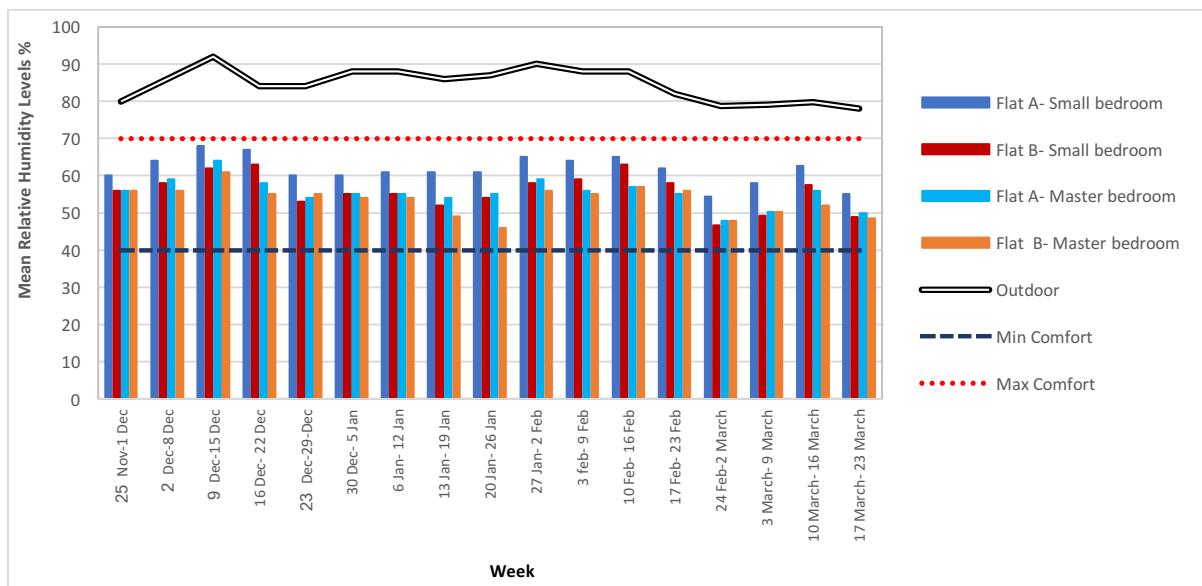


Figure 4. Weekly mean indoor RH levels against outdoor RH levels in small and master bedrooms in flats A & B

Table 2. Min, Max, Mean indoor air temperature and RH levels of the measured flats during the coldest week of winter, 17th Jan 2017 until 23rd Jan 2017.

Flats	Bedrooms	Temperature			RH Levels		
		Min	Mean	Max	Min	Mean	Max
Flat A	Small	19.1	20.6	21.6	47	63	76
	Master	20.2	21.9	23.2	40	57	70
Flat B	Small	16.7	17.1	20	48	54	65
	Master	14.5	16	19	42	46	51
Outdoor		-6.8	-0.2	6.8	48	85	100

Figures 5 and 6 illustrate the measured indoor air temperature and relative humidity levels against DB simulation results during the coldest week of the monitoring period. It can be seen that there is an acceptable correlation between the measured indoor air temperature and DB software generated air temperature. This proves that DB can be used as a valid software to perform the simulation modelling for the second phase of the project. In addition, this shows that the predicted building materials for the case study building (based on the 60s building material for the pre-cast concrete block) are also acceptable. Moreover, the measured indoor RH levels in all bedrooms were generally higher than the predicted results. Apart from the software and data loggers' accuracy, the water ingress issue in the flats might be one reason, is caused by the damaged external over cladding. Studies show that dampness can lead to mould growth on the building surfaces and the decrease in the effectiveness of the thermal insulation (Trotman et al., 2004) which is the case of the base case flats. The water also can be entrapped in the building materials and the indoor moisture can be appeared on the building fabric behind the insulation during the cold period as the building is internally insulated (De Selincourt, 2015). The occupants' lifestyle also has a significant impact on this issue, for example showering a few times a day in Flat A and once a day in Flat B and using washing machine every day in both flats. Although the bedrooms in Flat A are ventilated for one hour every day, the relative humidity levels are higher than Flat B as this property is occupied by a young family of five but Flat B has only one occupant.

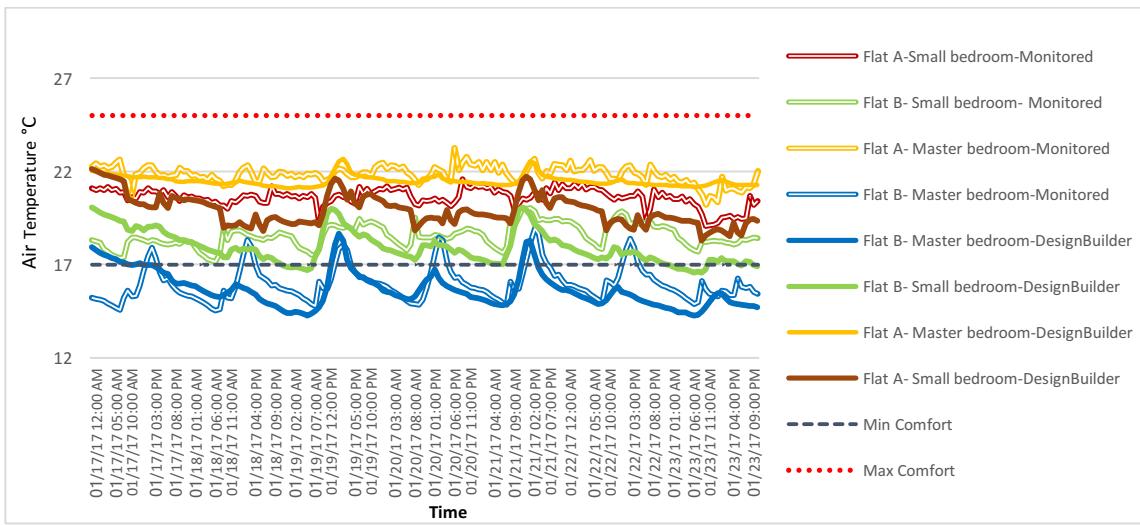


Figure 5. Indoor monitored air temperature against DB software predicted results in flats A & B bedrooms

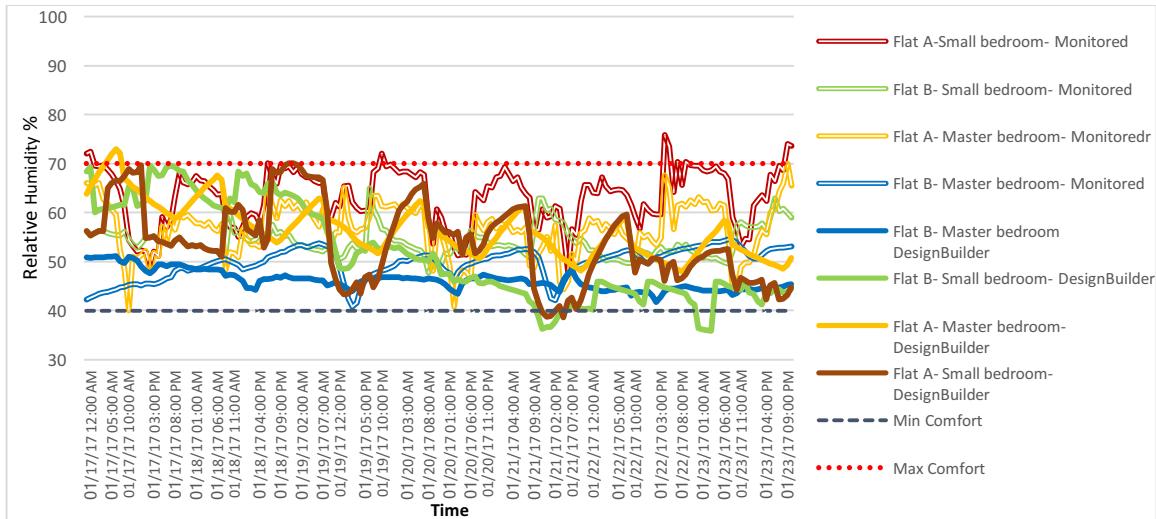


Figure 6. Indoor monitored RH levels against DB software predicted results in flats A & B bedrooms

The building simulation analysis shows that the average daily heating energy consumption of the small bedroom (non-problematic) and the master bedroom (problematic) of Flat A are 4 KWh and 10 KWh. This shows that the heating energy consumption in the master bedroom is higher than the small bedroom, probably to reduce the level of damp and condensation. In addition, 1.7 KWh of this energy in the master bedroom and 0.8 KWh in the small bedroom lose through infiltration because of the poor building fabrics. Moreover, as the total area of the master bedroom is 13 m<sup>2</sup> and the small bedroom is 10 m<sup>2</sup>, the problematic room uses more energy for heating to keep the indoor air temperature in an acceptable range. However, the energy consumption and the system loads in Flat B bedrooms are zero as the radiators are turned off because of the occupants' health issues although it is turned on in the rest of the flat during the day-time in the winter season. In addition, the heat loss from infiltration in this flat is 1.1 KWh in master bedroom and 0.6 KWh in small bedroom.

## Conclusion

This paper studies the thermal performance of a tower block in London Borough of Newham in two typical properties of the block as a sample. Field monitoring and simulation analysis were performed to assess the building performance (phase one). The focus of this research

was on the master and small bedrooms. Both flats have the water ingress issue in the same corners of the flats which is significant in the master bedrooms. The results of this research supports the argument that the dampness issues in the case study flats may be caused by the poor construction materials of the external walls. This is further elucidated as both indoor air temperature and RH levels of the rooms within both flats were usually in the acceptable range during the field monitoring period. However, the occupants were generally unsatisfied with the indoor environmental conditions. In addition, the occupants are unaware that their energy consumption behaviour and lifestyle might indeed add to this problem during the winter season. Raising awareness of occupants concerning energy consumption behaviour and the important role of programmed natural ventilation can reduce many of the issues experienced. However, the long-term solution is the energy efficient retrofit, which can essentially reduce damp and mould in the properties, while reducing the energy consumption of the block and providing a comfortable indoor environment. The second phase of this project focuses on the building performance optimisation and provides feasible and cost-effective recommendations for energy efficient retrofit for the domestic sector in LBN.

## Acknowledgment

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## References

- Bromley-dery, K. 2015. Home Energy Conservation Act (HECA) Return London.
- CIBSE 2016. Environmental Design, CIBSE Guide A. London, UK: Chartered Institution of Building Services Engineers.
- Colquhoun, I. 2008. *RIBA Book of British Housing: 1900 to the Present Day*, Oxford, Architectural Press.
- De Selincourt, K. 2015. The risks of Retrofit. *Green Building Magazine*, 25, 28-37.
- Department of Energy and Climate Change 2012. International aviation and shipping emissions and the UK's carbon budgets and 2050 target. London: The Department of Energy and Climate Change.
- Google. 2017. *The Site of a Tower Block in London Borough of Newham*. Google.
- Harrison, H. W. & De Vekey, R. C. 1998. *BRE Building Elements: Walls, Windows & Doors*, London, BRE Press.
- Hopper, J. 2012. Evaluating the Installation of Retrofitted External Wall Insulation - CIAT Student Award, Technical Report. London, UK: CIAT.
- London Borough of Newham 2007. Typical Floors Plans of the Tower Block in LBN. London: London Borough of Newham.
- London Borough of Newham 2016. Water Penetration Survey. London.
- Low Carbon Innovation Coordination Group 2012. Technology Innovation Needs Assessment (TINA)-Domestic Buildings- Summary Report.
- Malpass, P. & Walmsley, J. 2005. *100 Years of Council Housing in Bristol*, Bristol, UK, Faculty of the Built Environment, University of West England.
- Mayor of London 2015. RE:NEW- Helping to make London's homes more energy efficient. London: Mayor of London.
- Medhurst, J. & Turnham, C. 2016. Damp Survey for London Borough of Newham. London.
- Rickaby, P. 2011. GUIDE 1: introduction to the low carbon domestic retrofit guides. *Building Opportunities for Business*. 1 ed. London: Institute for Sustainability.
- Trotman, P., Sanders, C. & Harrison, H. 2004. *Understanding Dampness*, Watford, BRE Bookshop.
- Vilches, A., Padura, Á. B. & Huelva, M. M. 2017. Retrofitting of homes for people in fuel poverty: Approach based on household thermal comfort. *Energy Policy*, 100, 283-291.
- Walker, S. & Ballington, R. 2015a. Domestic Energy Efficiency in Newham Annual Report 2013-4. London.
- Walker, S. & Ballington, R. 2015b. LBN Annual Fuel Poverty Report 2013-14. London.

# Carbon Accounting

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# PLEA 2017 EDINBURGH

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## Assessing and Mapping the Carbon Foot-Print of A Campus Environment Using BIM and Geo-Spatial Techniques

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**Abstract:** The paper presents a case study of carbon foot-print assessment for an institutional campus located in the composite climate of India. The study deals with a 40-acre geography comprising of academic, residential, administrative and health-care buildings. Real-time operational energy consumption of the buildings over a period of 3 years, embodied energy, photo-voltaic power generation from roof-top collectors, water consumption and carbon sequestration potential of landscapes were collected through field studies. The paper presents characterization analyses of real-time energy consumption and carbon emissions and subsequently estimates the life cycle energy of buildings. The paper demonstrates the methodology adopted for geo-spatial mapping of the real-time and calculated data through this case study. The paper discusses the significance of developing such maps from a facility management perspective. Results obtained indicate that this approach not only helps with a holistic assessment of energy and environmental performance of campus infrastructure but also serves as a tool for cost-benefit and efficiency analysis of performance related retrofits.

**Keywords:** carbon footprint, thematic mapping, Building information modeling, GIS,

### Introduction

Balancing the carbon emissions and keeping in pace with progressive growth is a challenge faced by developing economies like India. By 2030, the world's population in cities will be consuming 73% of world energy, which accounts for 70% of CO<sub>2</sub> emissions (International Energy Agency, 2009). Building construction and usage consumes one-third of the primary electricity in India. Embodied energy and carbon is also a topic of rising importance. In fact, it is normally possible to reduce the embodied energy and carbon of a building or construction project by 10-20% without adding to the build cost. It is often 20-50% of the whole life (embodied + operational) carbon emissions of a new building (CircularEcologyLtd, 2015).

Carbon footprint is the total amount of land area required to assimilate the amount of CO<sub>2</sub> produced by a mankind during its life time, this may include systems, process, operations and maintenance (Wackernagel, 1996). The present concept of carbon footprint is taken as life cycle impact category indicator for global warming potential (Finkbeiner, 2009). Significant factors that affect the carbon emission include population, energy efficiency, energy structure and the model and scale of the economic development (Bing, 2011).

Dumfries and Galloway College (Gibson, 2010) conducted a detailed carbon footprint assessment starting with baseline calculations through detailed building audit that includes both energy audits and water audits to come up with some recommendations for the emission reduction.

Synergic use of Geographic Information System (GIS), Building Information Modeling (BIM) and Life Cycle Energy (LCE) assessment may provide a meaningful framework towards sustainability. Building Information model, which is a rich model, comprises of individual building, site or GIS object with attributes that define the detailed description and relationships. BIM significantly improves the process of LCA assessment this can be used as the information source while transferring Building information into the geo spatial environment. Significant developments in the conceptual framework have been evolved, which are used by companies to perform Building information modelling based sustainability (Azhar, 2011). Information from both BIM as well as associated Geographical data can increase the success of asset management. However, taking into account the integration of BIM and GIS, there are many issues that are still under research. However, the merging creates an even more powerful tool that is used in the AECO/FM industry (Fosu et al, 2015).

This paper assesses carbon footprint of a campus environment and maps it using a geographic information system. It is intended towards developing a comprehensive method to identify stressed areas and serve as a holistic platform for facility managers in energy efficiency related decision-making.

## **Objectives**

The paper adopts an LCE based approach along with the help of BIM and geo-spatial analysis tools for assessment and mapping. The objectives of the study are (a) to assess the LCE and carbon emissions of the buildings through field studies and (b) to carry out geo-spatial assessment and mapping of emission sources and sinks to facilitate multi-attribute decision-making.

The scope of the study is limited to carbon footprint assessment of a 40-acre geographic extent within an institutional campus. The study considers environmental impact and embodied energy data available from international databases.

## **Details of the study:**

The case study site encompasses academic, residential, administrative and health-care buildings which form part of a 340-acre residential campus located in Roorkee, India ( $29.9^{\circ}\text{N}$   $77.9^{\circ}\text{E}$ ). The site characterises a composite climate. Summers experience mean monthly outdoor dry-bulb temperatures ( $T_{\text{out}}$ ) of about  $29.5^{\circ}\text{C}$  with a mean maximum and minimum  $T_{\text{out}}$  of about  $40^{\circ}\text{C}$  and  $20^{\circ}\text{C}$  respectively. Winters experience mean monthly  $T_{\text{out}}$  of about  $12^{\circ}\text{C}$  with a mean maximum and minimum  $T_{\text{out}}$  of about  $19^{\circ}\text{C}$  and  $4^{\circ}\text{C}$  respectively. Fig. 1 represents the base map of the study area.

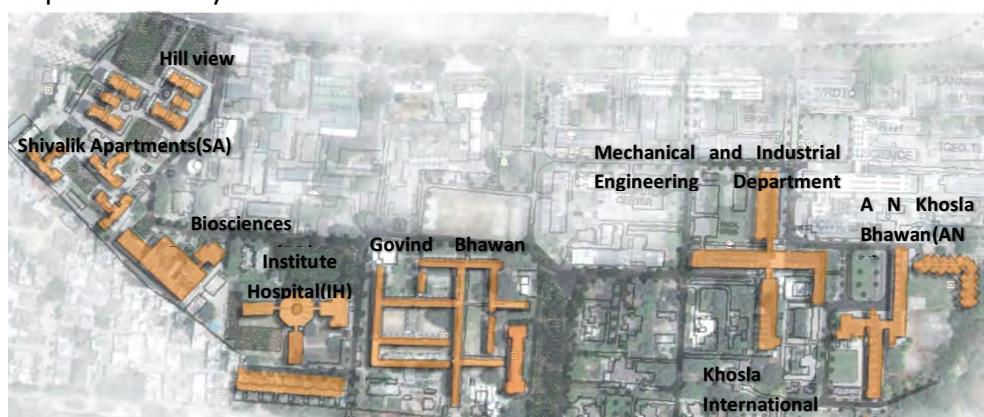


Figure 1 Base map showing the study area

## Description of Buildings

The study area includes the following 8 buildings – 2 number of 7-storied residential apartments (HA), 3 number of 7-storied residential apartments (SA), an international student house (KIH), a married student's hostel A N Khosla(ANK), a student dorm and hostel building (GB), a 2 storied academic building (MIED), a 6-storied academic building (BD) and a 2-storied Hospital building (IH). Apart from this, the site consists of 15 individual faculty residencies which are ground+1 structures. Table 1 provides further details of the buildings.

Table 1 Description of Buildings

S.no	Abbreviation	Name	Floor Area	Number of Floors
1	HA	Hillview Apartments	150 m <sup>2</sup> / unit	7
2	SA	Shivalik Apartments	135 m <sup>2</sup> / unit	7
3	BD	Biotech Department	8000 m <sup>2</sup>	6
4	IH	Institute Hospital	4800 m <sup>2</sup>	3
5	GB	Govind Bhawan	25000 m <sup>2</sup>	3
6	MIED	Mechanical and industrial engineering dpt.	10000 m <sup>2</sup>	3
7	KIH	Khosla international house	2300 m <sup>2</sup>	3
8	ANK	A N Khosla	1500 m <sup>2</sup>	3

A wide variation in occupant density, time and pattern of occupancy and the clothing insulation values among these buildings. The building information such as type construction; materials have been assessed through field survey.

## Embodied Energy Assessment

A detailed 3-D model of the 8 major buildings were prepared using Autodesk Revit software tool. Detailing of building elements were done based on the construction drawings and physical field audits. An estimate of material quantities was drawn from the building information model (BIM) using which embodied energy and the related environmental impacts of the building materials were calculated using Tally software tool. Tally tool utilizes a custom designed LCA database that combines material attributes, assembly details, engineering and architectural specifications with environmental impact indicators adapted from GaBi database. These relationships were used to quantify environmental impacts across several categories, such as embodied energy and global warming potential. The workflow consisted of defining reference and take-off information for each entry through which material quantities were calculated. Fig 2 shows an example of the environmental impact

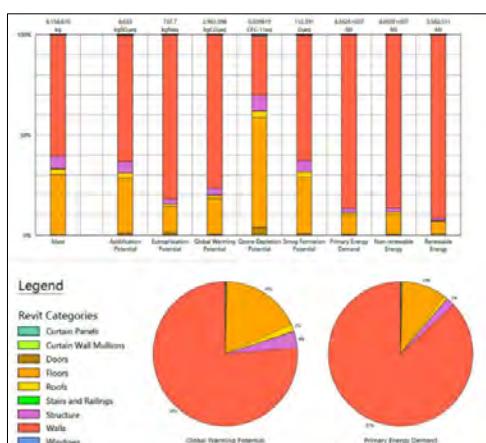


Figure 2 Environmental impact results as per Revit category for IH building

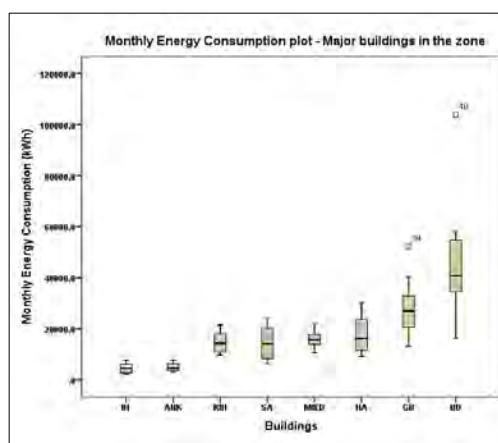


Figure 3 Monthly Energy consumption plot of buildings

data obtained for IH building. Similar such analysis was carried out for other buildings in the study area.

### Operational energy assessment

Operational energy values over two-year duration were taken for the characterization analysis of Energy consumption. Fig 6 shows the statistical summary of monthly operational energy consumptions of these buildings.

Fig. 5 shows the relation between monthly operational consumption (averaged over the past two years) and the monthly mean  $T_{out}$ . A strong positive correlation ( $r^2$  range = 0.6-0.8) was observed for almost all buildings which signify a strong dependence of operational energy consumption on outdoor climate. However, in the case of GB, the variation in the occupancy data and the activity type and schedule results in a relative weak correlation ( $r^2$  = 0.35). These values were used to validate the output of the simulated operational energy.

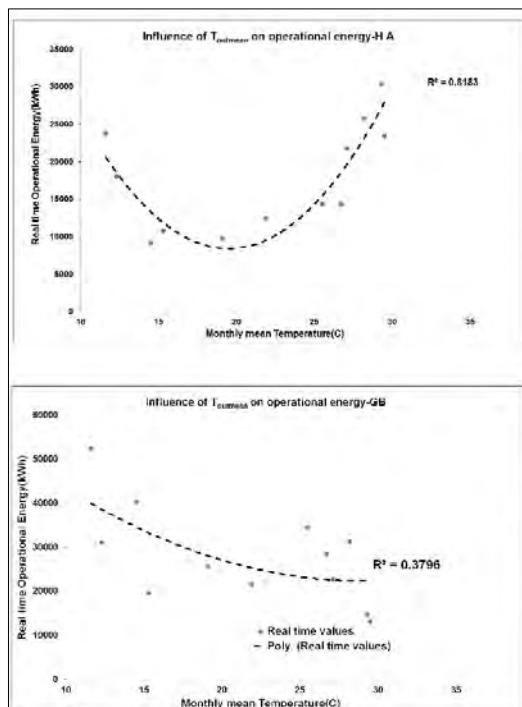


Figure 4 Influence of outside mean temperature on energy consumption data of HA & GB Buildings

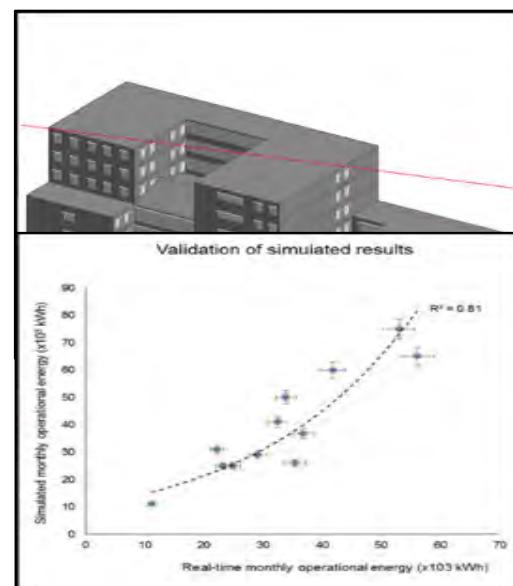


Figure 5 Design builder model and validation graph

### Simulation of Operational Energy

Based on the field data and drawings/specifications the buildings were modeled in Design Builder software tool. This tool interfaces with Energy Plus dynamic thermal simulation engine for comfort and energy simulations. Field investigations were carried out which involved questionnaire surveys and walk-through assessments to identify the operational pattern of building and systems, activity schedules, internal connected loads and the equipment usage pattern.

Connected loads, internal lighting and equipment were modeled as existent in the actual conditions. Complete building energy simulation was performed using weather data from a nearest weather station (Saharanpur, UP, India). To check the validity of the simulation model, the results obtained were compared with the field data. The predicted results agreed

well with the actual data ( $r^2 = 0.9$ ) for all the buildings under study. Figure 8 shows a snapshot of design builder model for BD building and the validation plot for the same.

### Computation of Life Cycle Energy

The Embodied energy values and operational energy values were used to compute the total LCE of the buildings under study. Table 1 shows the Embodied, Operational energy of the building normalized with the corresponding floor areas and Life Cycle Energy of the buildings estimated for 50 years' span. In addition, the table presents an estimate of equivalent CO<sub>2</sub> emissions corresponding to the embodied and operational energies.

Table 2 Energy values of Buildings

S.no	Name	EE(x10 <sup>3</sup> MJ)/m <sup>2</sup>	EPI(kwh/m <sup>2</sup> /yr)	LCE-50 yrs.(x 10 <sup>6</sup> MJ)	EC (tCO <sup>2</sup> eq)	OC (tCO <sup>2</sup> eq)	LC-50yrs (x10 <sup>3</sup> tCO <sup>2</sup> eq)
1	HA	8.65	37	250.39	319	280	41
2	SA	10.36	33	241.17	305	253	37
3	BD	14.79	124	510.94	303	776	105
4	IH	10.43	25	106.54	148	89	14
5	GB	5.29	14	447.63	492	495	71
6	MIED	5.46	18	211.40	243	252	36
7	KIH	9.35	35	219.93	204	275	38
8	ANK	12.78	27	57.14	72	58	9

EE - Embodied Energy, EPI- Energy Performance Index, LCE - Life Cycle Energy, EC- Embodied Carbon  
OC- Operational Carbon, LC- Life Cycle Carbon

The operational energy values in Mega joules were converted to tons of CO<sub>2</sub> values in order to get the total carbon dioxide emissions onto the atmosphere. While all stages of a building's life cycle (including construction and demolition) produce carbon emissions, the building's operational phase use - heating, cooling, ventilation, lighting and appliances - accounted for about 80% of emissions.

### Gains from solar offsets

The buildings under investigation harness renewable energy in the form of rooftop solar photovoltaic units, solar concentrators for cooking and solar water heating systems. Solar photovoltaic units are installed on the rooftops of academic buildings. Solar concentrators are installed on the hostel buildings, while solar water heaters are installed on hostels and residential apartments. PV systems have been connected to micro grid power of the campus. Existing geysers have also been connected to the solar water heating systems for use during periods of low and poor heating/sunshine due to fog or excessive cloud cover. The roof top solar energy collection systems were found to offset about 15% of the energy usage state grid. Fig 6 shows the solar energy offsets for two buildings for the next 50 years' life cycle.

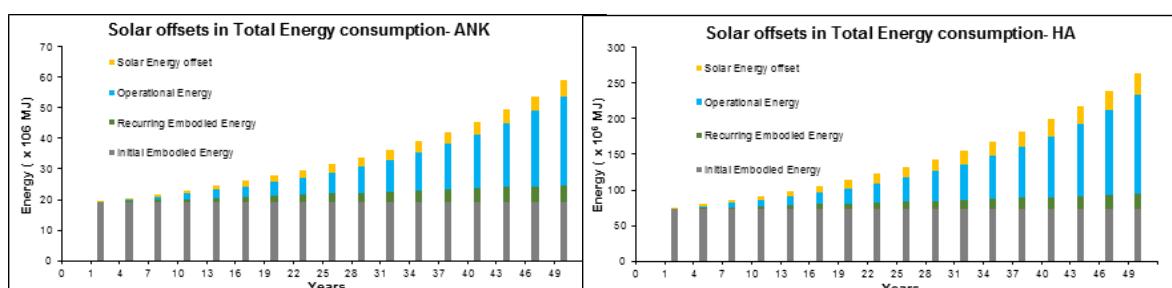


Figure 6 Solar energy offsets for the entire life cycle of the building

## Water consumption data

Water consumption in the campus has been calculated as per the baseline values provided by Bureau of Indian standards (BIS, 1993). The minimum requirements for water supply for residences is 135 litres per head per day (lpd), hospitals 340 lpd and institute 45 lpd. The total water consumption in the area is 302.7 kilo litres per day and 1, 10,469.5 kilo litres per year excluding the water consumption towards gardening.

## Carbon sequestration of landscape elements

To study the total amount of carbon sequestered in the study area, a simple random sampling method has been adopted. The biomass of the trees was first calculated by non-destructive method for which the tree diameter at breast height (DBH) approximately 1.3 meters, height of the tree by theodolite at DBH and the density of the trees were considered (Brown, 1993). The mathematical equation eq. 1 developed by Brown (Brown, 1989) has been adopted

$$Y = \text{Exp. } \{-2.4090 + 0.9522 \ln (D^2 \times H \times S)\} \quad (1)$$

Where, Y is the above ground biomass (kg), H is the height of the trees (meter), D is the diameter at breast height in cm. and S the wood density ( $\text{gm}/\text{cm}^3$ ). Wherever the wood density of tree species was unavailable. The standard average value  $0.6 \text{ gm}/\text{cm}^3$  were taken (Warren, 2001). Below ground, biomass was calculated considering 15% of the above ground biomass (MacDicken, 1997). The amount of carbon in a tree is approximated to 50% of the total biomass of the tree with an error of  $\pm 5\%$  (Sean, 2012). 1 ton of carbon is equal to 3.666 tons of CO<sub>2</sub>; this denotes the weight of carbon dioxide (44) divided by the atomic mass of carbon (12). The total amount of carbon sequestered in the 40-acre area from trees is 10.54 tons i.e., 38.57 tons of CO<sub>2</sub> and the amount of carbon sequestered by the 2.86 acre maintained turf grass in the area is 1.31 tons i.e., 4.8 tons of CO<sub>2</sub> with the value per acre taken as 0.46 tons.

## Mapping of CO<sub>2</sub> Emissions and Sequestration

A thematic map is a visual representation of characteristics of a given geographic location. The existing parameters and the assessed parameters were taken to the GIS software to create the thematic maps. A single field from a single layer of data provided with the sample data installed with ArcGIS and QGIS was required for the process. The geo-coordinates of the major control points taken from the study area were used for the geo-referencing of the campus base map.

Another way of representing the maps are through the contour maps. The carbon sequestration values per year and the simulated values are taken to the GIS software in which these point values are interpolated to obtain this discrete map of various range of values. Contour maps shown in Fig. 7 represent the different layers - Embodied carbon emissions, operational carbon emissions and the carbon sequestration by the landscape elements are shown in 3D exploded view.

Table 3 Split up ratio of Lighting, HVAC and Connected loads

Name	HA	SA	BD	IH	GB	MIED	KIH	ANK
Lighting : HVAC : Connected loads (tCO <sub>2</sub> eq)	83:	83:	78:	19:	148:	70:	45:	16:
	108:	108:	232 :	46:	05:	115 :	140 :	20:
	89	89	456	24	342	77	90	21

The values of building's embodied carbon emissions ranging from 72 tons of CO<sub>2</sub> (tCO<sub>2</sub>eq) to 492 tons of CO<sub>2</sub>, operational carbon emissions values ranging from 58 tCO<sub>2</sub>eq to 776 tCO<sub>2</sub>eq and their sum to get the total carbon emissions of the major buildings in the study area. The small residential blocks of G+one, which are also a part of the zone, have embodied and operational carbon emission values of 10 tons of CO<sub>2</sub>. The landscape elements mainly large trees, plants and lawns collectively sequester around 43 tons of CO<sub>2</sub>eq, which is 4 times that of the CO<sub>2</sub> emitted by the smaller residential blocks. However, the emissions by the major buildings exceed the amount absorbed by the landscape surrounding them. The operational carbon emissions are majorly due to the lighting loads, heating, ventilation and air conditioning loads and the internal connected loads. Table 3 shows the ratio of this split up of carbon emissions.

The exploded view of contour map in Fig.8 illustrates the effect of carbon emissions due to lighting and HVAC loads on the environment and carbon sequestration values of the landscape elements. There are many loads, which are lesser than the carbon sequestered by the landscape elements. The proliferation in the usage of HVAC and newer constructions of 6 to 7 storeyed buildings for the last 15 years increased the emissions into the environment. This condition was further worsened by the cutting down of the large trees in these areas. The vegetation including small and large trees, shrubs, bushes and lawns around these major buildings, which sequester the emitted carbon dioxide, though much lower quantity than the total emitted value, play a major role in the overall carbon reduction. Thematic maps prepared clearly identifies the most stressful area in the zone, so that more vegetation can be planted around them.

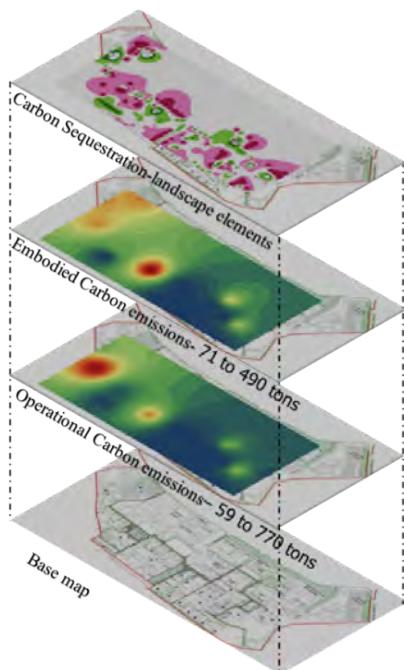


Figure 7 3-D exploded view of Contour maps - Embodied carbon and operational carbon emissions vs carbon sequestered

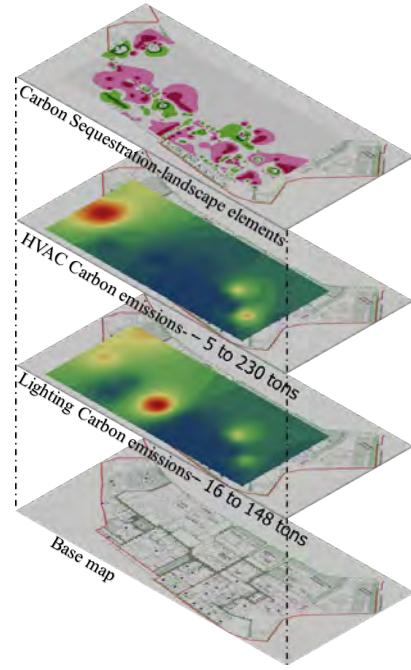


Figure 8 Exploded view of contour maps showing the carbon emission due to lighting and HVAC

## Discussion and Conclusions

The paper dealt with carbon footprint assessment and mapping of a 40-acre neighbourhood in an institutional campus. Embodied and operational energy characterization of major built structures in the study area has been carried out based on which the life cycle energy has

been estimated. Embodied energy of the buildings in the study area varied from  $5.3 \times 10^3$  MJ/m<sup>2</sup> for student hostels (GB) to  $14.8 \times 10^3$  MJ/m<sup>2</sup> for the academic building (BD). The EPI of buildings varied from 14 kWh/m<sup>2</sup>/y for student hostels (GB) to 124 kWh/m<sup>2</sup>/y for the academic building (BD). CO<sub>2</sub> offset provided by roof top solar collectors was estimated to be 950 tCO<sub>2</sub> per year. An assessment of embodied and operational carbon emissions as well as carbon sequestration by the landscape elements surrounding the buildings have been presented. We found the magnitude of carbon emissions from buildings to be so large for sequestration by the available trees and greeneries in the within the study area.

The paper also discussed the significance of developing contour maps and thematic maps of energy and carbon foot print from a facility management perspective. Results obtained indicate that this approach not only helps the sustainability assessment in a holistic manner but also serves as a decision making tool for cost-benefit and environmental analysis of performance related retrofits. The thematic maps provide an estimate of the gap between notion of carbon neutral developments and typical neighbourhood level emissions in the current day. The results highlight the need for improving embodied and operational energy efficiencies in order to minimize the carbon emissions and enhance the carbon sequestration potential of carbon sinks.

Further studies on larger geographic spread considering micro and macro-level factors affecting carbon footprint. Recent developments in BIM and Geospatial techniques will facilitate the possibilities of such large-scale studies adapting a same approach.

## Acknowledgement

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## References

- Azhar, S., 2011. Building Information Modeling BIM: Trends benefits, risks, and challenges in the AEC industry. *Leadership and Management in Engineering*, pp. 241-252.
- Bing, Y., 2011. Research and Development of Carbon Footprint Analysis In Hunan Province. *Energy Procedia*, Volume 5, pp. 1210-1217.
- BIS, 1993. In: "Indian Standard CODE OF BASIC REQUIREMENTS FOR WATER SUPPLY, DRAINAGE AND SANITATION," BUREAU OF INDIAN STANDARDS. Delhi: s.n.
- Brown, S., 1989. *Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data*.
- Brown, S., 1993. Estimating Biomass and Biomass Change of Tropical Forests: a Primer. FAO - Food and Agriculture Organization of the United Nations.
- CircularEcologyLtd,2015.[Online]Availableat: <http://www.circularecology.com/embodied-carbon.html>
- Finkbeiner, M., 2009. Carbon footprinting- Opportunities and threats. *International journal of Life Cycle Assessment*, pp. 91-94.
- Fosu et al, 2015. *Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) – a literature review and future needs..* Eindhoven, The Netherlands, s.n.
- Gibson, L., 2010. *Carbon Footprint Assessment for Dumfries & Galloway College (Dumfries Campus)*, Dumfries: s.n.
- International Energy Agency, 2009. *World Energy Outlook*, Paris: s.n.
- MacDicken, K., 1997. A guide to monitoring carbon storage in forestry and agro forestry projects.," Winrock International Institute for Agricultural Development.
- Sean, C. T., 2012. Carbon Content of Tree Tissues: A Synthesis. In: *Forests, Vols. ISSN 1999-4907, no. 3, pp. 332-352*. s.l.:s.n.
- Wackernagel, M. & R. W. (., 1996. our ecological footprint: reducing human impact on the earth, gabriola Island: New society publishers.
- Warren, A., 2001. Carbon Sequestration Potential of Trees in and around Pune City.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Development of a Framework for Carbon Footprint Assessment of Building construction systems

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**Abstract:** This paper reviews the current industry practices and emerging construction systems in India indicates a gradual shift from conventional construction practices to industrialised modular approaches with emphasis on lean construction. This has transformed the building construction from a predominantly on-site process to more industrialised de-centralised process. Evidence from literature highlights the potential savings in material resources, time and manpower. However, standardized framework to document, analyse and compare environmental benefits of such emerging alternates is not available. In this context, this paper attempts to develop a customized framework suitable for such assessment. It is based on the Life cycle energy assessment method with exclusive focus on factors that differentiate the environmental performance of the emerging construction systems from the conventional ones. The framework is developed based on primary data collected from on-going and completed construction projects and structured interviews conducted with construction industry professionals. The framework has three dimensions –design, off-site manufacture and fabrication, on-site construction and assembly. Each of these dimensions comprise of a stratified four-tiered assessment – manpower efficiency, material/resource efficiency, process efficiency and temporal efficiency. The study concludes, precast construction system has low CO<sub>2</sub> impact due to material efficiency (reduction), time efficiency and manpower efficiency.

**Keywords:** Low-Carbon alternatives, Construction Industry, Lean Construction, CO<sub>2</sub> emission, Resource efficiency

### Introduction

Global climate change is one of the significant challenges confronted by us. About one third of the CO<sub>2</sub> emissions leading to climate change, about 3 Gt/yr (Levine, 2007), has been attributed to building segment. This necessitates a critical review and assessment of the building's life cycle from design conception to construction, operation and post-service life. Carbon footprint (CF) assessment is one of the best process to calculate the environmental impact and climate change. By 2030, building sector in India is estimated to experience 500% increment of built floor area (CWF, 2010). This provides an estimate of possible increase in CO<sub>2</sub> emissions from these yet to be built developments. While it portrays the challenges faced by the Indian construction industry on one hand, it also portrays the potential ways of minimizing the emissions through efficient interventions.

Indian construction industry has seen the emergence of several materials and construction systems in the last two decades. The building materials technology promotion council (BMTPC) provides a comprehensive list of such systems (MHUPA, 2015). Such emerging construction materials and technologies are effective in terms of time, manpower and resource reduction (Barde, et al., 2014). Each of these effective factors impact the overall carbon footprint of these technologies. For conventional systems, generally factors like time, logistics and manpower have a negligible share in carbon emissions (Chani, et al., 2003). However, a detailed assessment of these aspects for new and emerging systems is not available in the Indian context. This necessitates a detail study and analysis on these factors to facilitate comparison of carbon footprint between conventional systems and emerging technologies.

This study is intended to investigate the impact of these factors on the overall carbon footprint of the system and develop a comparison between conventional and emerging construction systems. The main *objectives* of the study are (1) to categorise various activities associated with pre-construction/construction phases and document associated carbon emissions (2) to develop a framework for assessment and comparison of carbon emission from construction processes and demonstrate its application through a case study. It is limited to multi-storeyed residential construction in urban Indian locale.

## Methodology

The study has started with reviewing literature and market survey on residential building construction practices in India adapting conventional and emerging technologies. Various activities associated with pre-construction/construction phases which may affect the CO<sub>2</sub> emission are identified through field studies and focus group discussion with construction industry professionals. Pilot studies are done to access the impact of each factors in terms of the whole system. Three dimensions contributing to carbon footprint of building construction system - design, off-site manufacture and fabrication, on-site construction and assembly, are identified. Based on these primary assessments, an evaluation framework is developed which can assess these construction systems. The application of the framework is demonstrated using three live case studies involving conventional as well as emerging construction systems.

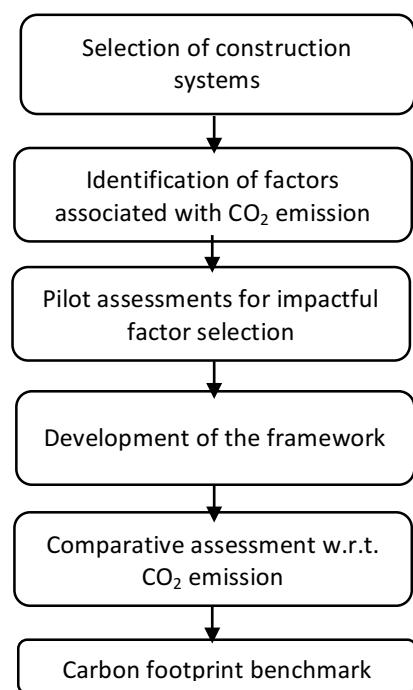


Figure 1: Methodology

## Various construction Technologies in India

BMTPC enlists eleven emerging construction technologies in residential building sector of India (MHUPA, 2015). Through a review of literature and a detailed market research on building materials, practices and demand, two of these technologies – reinforced concrete (RC) shear wall system and precast large concrete panel system – are found to have a wide-spread outreach for both low-income as well as mid and high-income group housing projects. RC shear wall system is increasingly being adopted across the country for various scales of buildings and precast system is an emerging lean system (Barde, et al., 2014) which is less resource, labour and time intense. Both these systems have a huge potential for deployment

across the country. This study presents a comparison of carbon footprint of these two systems with that of a conventional technique – RC frame construction with wet masonry filler wall system using.

#### ***RC frame construction with wet masonry filler wall system***

RC frames with unreinforced masonry infill walls is one of the widely present construction technology in India. In this system, the load is carried by the RC (Reinforced concrete) frame which is the combination of beams and column (where beams transfer the load to the column which transfers the load to the foundation) and non-load bearing walls are made from building blocks bound together by mortar (Yakut, 2004). The common materials of masonry construction are brick; stone; concrete block, glass block etc.



Figure 2: RC frame with brick as filler block (Source: <http://www.world-housing.net>)

#### ***Monolithic concrete construction using Aluminium Formwork (cast in-situ)***

Last few decades, this system is adopted by many construction companies throughout India for residential and mass housing project. This system mainly works as a monolithic unit. It is fast, simple, adaptable and cost – effective. Unlike traditional RCC framed construction of columns and beams, all walls, floors, slabs, columns, beams, stairs, together with door and window openings are cast-in-place monolithically using appropriate grade of concrete in one operation (MHUPA, 2015).



Figure 3: Monolithic concrete construction (Source: <http://www.mhupa.com>)

#### ***Precast Large Concrete Panel System (PLCP)***

Precast technology is effective in terms of affordability, mass production, faster and lean construction. As per the construction practices followed in India, Precast members are manufactured and cured in the factory. Heavy duty cranes lift the panels and components are placed in the required location. Members/panels are joined together by dowel tubes and 'stitching' (cast in-situ) (Barde, et al., 2014). The Precast technology has high quality output, less energy consumption for manufacture and fabrication, less waste generation, less labour intense, less time and resource requirement.



Figure 4: precast system (source: [http://www.cpci.ca/en/precast\\_solutions/total\\_precast/](http://www.cpci.ca/en/precast_solutions/total_precast/))

## Defining the System

Every construction technique can be interpreted as a system. Based on the literature review and primary studies, a construction system can be divided into Off-site and on-site phases. The off-site phase can be further divided into Design and Fabrication. All these phases or processes has various factors which are related to CO<sub>2</sub> emissions. These factors are material resource, Energy, Infrastructure, Manpower, time and Logistics. This system can be represented by following tree diagram (see figure 5). For this study, Fabrication implies the precast panel fabrication.

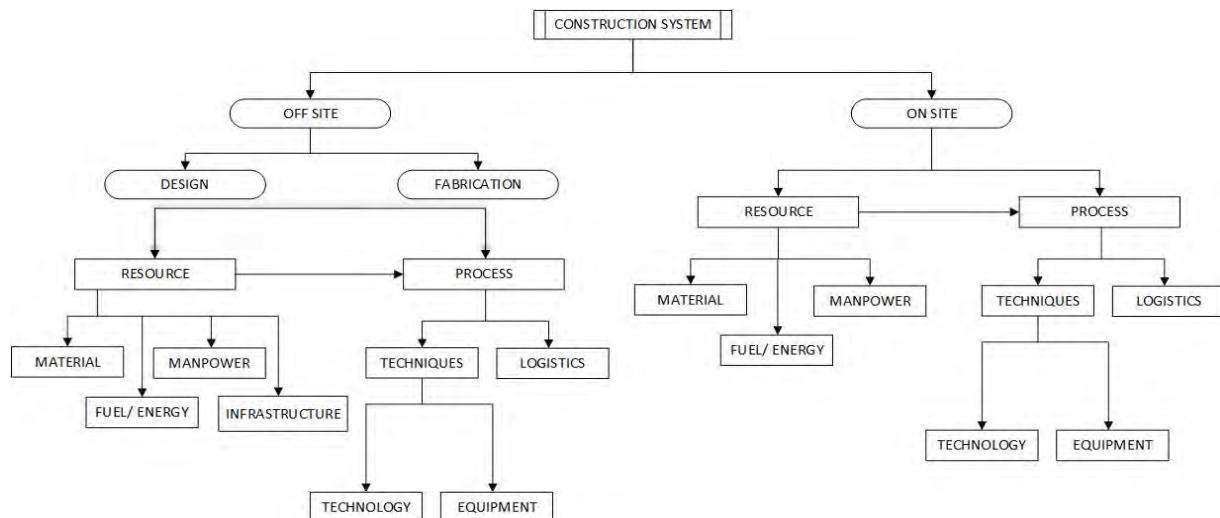


Figure 5: Construction system structure (source: Author)

## Various factors associated with CO<sub>2</sub>

New emerging materials and technologies are effective in terms of Time, Manpower and Resource reduction which impact the overall carbon footprint. Every phase/stage can be divided into various factors.

Table 1: Various factors associated with CO<sub>2</sub>

Stages		Efficiency		Scale		Scenarios											
Design	D	ManHour	T	Low	High	D_L			D_H								
		Infrastructure	I			T_LL	T_LH	T_HL	T_HIH								
Fabrication	F	Process	P	Low	High	F_L								F_H			
		ManHour	T			P_LTLL	P_LTLLH	P_LTLL	P_HTLLL	P_LTLLH	P_HTLLLH	P_HTLLL	P_HTLHLL	P_HTLHLLH			
		Logistics	L														
Construction	C	Process	P	Low	High	C_L								CH			
		ManHour	T			P_LTLLM_L	P_LTLLM_H	P_HTLLLM_L	P_HTLLLM_H	P_HTLLLM_H	P_HTLLLM_L	P_HTLHLLM_H	P_HTLHLLM_L	P_HTLHLLM_H			
		Logistics	L			P_LTLLMH_L	P_HTLLLMH_L	P_HTLLLMH_H	P_HTLHLLMH_L	P_HTLHLLMH_H	P_HTLHLLMH_L	P_HTLHLLMH_H					
		Material	M														

For example, Design stage has 2 major factors: Man-hour (T) and Infrastructure (I). The combination of Low to High CO<sub>2</sub> emission of each factor will impact the Low (D<sub>L</sub>) to High (D<sub>H</sub>) emission of the whole Design Stage (see figure 6). Design phase has 4 possible combination from low to high. Similarly, Fabrication and construction phases have 8 and 16 combinations. This helps to scale and compare the CO<sub>2</sub> emission of these systems.

### **Carbon assessment framework**

The framework is formulated to analyse the CO<sub>2</sub> emissions for each factor related to the construction systems. It has three dimensions –Design, off-site Fabrication, on-site Construction/Assembly. Each of these dimensions can be stratified into four-tiers – Manpower efficiency, Material/Resource efficiency, Process efficiency and Temporal efficiency. These factors may have marginal to significantly high impact on the carbon emission of entire construction. Table 2 discusses the various emission factors and their sources which has been considered for developing of the framework.

Table 2: Various CO<sub>2</sub> Emission factors (used for CO<sub>2</sub> emission calculation)

Item/ Process	Emission factor	Unit	Source
Man-Hour (Design)	1.59	KgCO <sub>2</sub> /day	> World Bank group, 2016 for low and medium income group
Man-Hour (Construction)	0.904	KgCO <sub>2</sub> /day	> Auroville Earth Institute report on Embodied Energy in Building Materials and Technologies for Green Residential Buildings, 2013
Purchased Electricity	0.82	CO <sub>2e</sub> kg/kWh	>CO2 Baseline Database for the Indian Power Sector User Guide Version 10.0 December 2014, Government of India Ministry of Power Central Electricity Authority
Diesel Fuel Oil	2.653	CO <sub>2e</sub> kg/l	>ISO 14064-1:2006 - Greenhouse gases
Heavy Duty Vehicles	3.59	CO <sub>2e</sub> kmpl	>Dr. B. Krishna Reddy, Mrs. T.Raghavani, FUEL CONSUMPTION MODEL OF LIGHT COMMERCIAL TRUCKS, International Journal Of Science Technology & Management, 2015
	0.762	CO <sub>2e</sub> kg/km	> "Emission Factor development for Indian Vehicles "as a part of Ambient Air Quality Monitoring and Emission Source Apportionment Studies Project Sponsored by CPCB/ MOEF
Cement	0.83	CO <sub>2e</sub> kg/cum	> Inventory of Carbon and Energy (ICE database), version 2.0, 2011, university of Bath
Sand	0.005	CO <sub>2e</sub> kg/cum	
Aggregate	0.005	CO <sub>2e</sub> kg/cum	
Concrete	0.13	CO <sub>2e</sub> kg/cum	
Steel	1.77	CO <sub>2e</sub> kg/kg	
Concrete block	0.074	CO <sub>2e</sub> kg/nos	

In Design stage, there are two major factors associated: Man-hour and Infrastructure. Man-hour emission has been calculated by multiplying the consumption emission of human energy with the total man-hour for each of the stages. This per capita consumption value has been taken as 1.59 kg/day/person (see Table 2). For design infrastructure footprint estimation, the share of man-hours and corresponding building usage is determined from the energy

consumption of the office. In this paper, the estimates are based on annual energy consumption per square meter of commercial building in India which is then multiplied by the CO<sub>2</sub> emission per kWh electricity India value (see Table 2).

In Fabrication stage, there are three factors associated: Process, Man-hour and Logistics. For process the estimates are calculated by multiplying total power consumption from the fabrication factory/yard and electricity emission factor. Logistics is calculated by multiplying distance covered by the truck (full trip) and emission rate of CO<sub>2</sub> in kg per Km distance. Man-hour is calculated by multiplying the consumption emission of human energy (construction labour) value with the total man-hour for each of the stages. This per capita consumption value has been taken as 0.904 (see Table 2).

In Construction stage, there are four factors associated: Process, Man-hour, Logistics and Material embodied energy. Material embodied energy is calculated by multiplying Quantity and emission factor for individual materials. Rest of the factor calculations are as per the above method. The Total emission for each phase gives the Low to High CO<sub>2</sub> emission by the whole system and its used to compare one system to another.

### **Application of the framework for comparing three construction systems**

The application of the framework is demonstrated by comparing a conventional system with that of cast-in-situ RC system and a precast construction. The conventional case is a residential project (G+3) with 500 units (32 buildings) and construction duration for the total project is 30 months. Here the system comprises of RC frames with Concrete block infill walls and with no fabrication stage for this case. For cast-in-situ RC system, a Residential project (G+11) with 770 units is constructed. It uses aluminium formwork system and the construction duration for the total project in 30 months. For Precast panel system, a residential project (G+23) with 976 units is taken. The construction duration for the total project in 39 months. The normalization factor for the study is per flat unit.

### **Comparison and analysis**

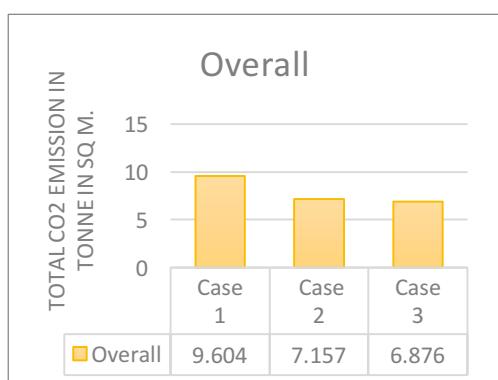


Figure 6: Overall CO<sub>2</sub> emission

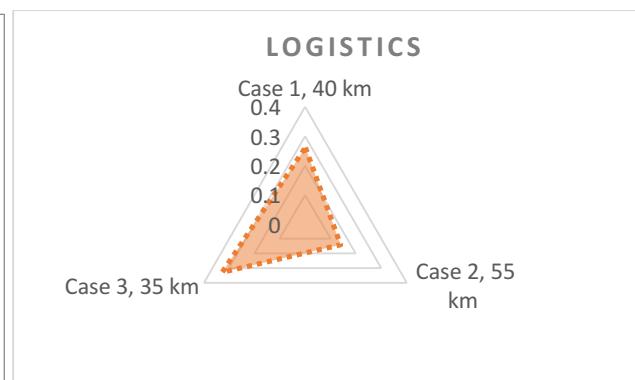


Figure 7: Logistics CO<sub>2</sub> emission

Research outcome suggests, there is overall 30% reduction in CO<sub>2</sub> emission for Precast panel system. This situation arrives due to 20-30% material reduction and 30-40% man-hour reduction. Figure 6 shows the CO<sub>2</sub> emission level of these material. For logistics emission calculation, CO<sub>2</sub> increases with the distance travelled. 50% of CO<sub>2</sub> emission reduction can be achieved by decreasing the distance by 15-20 km. For Man-Hour emission calculation, almost 30-40% of co2 emission reduction can be achieved by using precast mode of construction.

Table 3: Framework analysis- Comparison of the cases

Stages		Efficiency		Case 1 (RC Frame)	Case 2 (Aluminium Formwork)	Case 3 (Precast)	Scale
Design	D	Man-Hour	T	$T_{HIL}$	$T_{HIL}$	$T_{UL}$	Low
		Infrastructure	I				
Fabrication	F	Process	P	-	-	$P_LT_{HL}$	Mid
		Man-Hour	T				
		Logistics	L				
Construction	C	Process	P	$P_H T_H L_H M_H$	$P_H T_L L_L M_H$	$P_L T_L L_L M_H$	High
		Man-Hour	T				
		Logistics	L				
		Material	M				

Table 3 shows the complete framework and the scale of CO<sub>2</sub> emission for various live projects/cases. Low to high CO<sub>2</sub> emissions are represented by the colours mentioned in the framework. For case 1, overall CO<sub>2</sub> emissions is high due to max Man-hour, high amount of material uses. For the case 2, CO<sub>2</sub> emissions is High due to increment of excess amount of steel. Whereas the Man-hour and Logistics are Low in case of case 2 as compare to case 1. For case 3, Overall CO<sub>2</sub> emissions are low due to process and resource efficiency. Although case 3 has fabrication stage emission, CO<sub>2</sub> emissions in construction makes it overall Low by decreasing process, material and Man-hour emission.

### Summary and conclusion

The efficiency of the framework can be assessed by comparing the 3 construction systems. But for few of the factors, associated with the various pre-construction and construction stages, can vary irrespective of the construction types. For example, logistics does not really depend on the construction system type: It solely depends on the distance covered, vehicle type, occupancy efficiency and fuel efficiency etc. For pre-cast construction system CO<sub>2</sub> emission is lower than the other due to material efficiency (reduction), time efficiency and labour efficiency. 20-30% of wall material reduction is possible for Precast system due to lean strategies like modular wall panel design and reduction in material wastage. Precast system can reduce the overall CO<sub>2</sub> emission by 30% in comparison to conventional system.

The framework can be further improved by calculating actual field data for Labour emission and Transportation emission which is here taken from the literature and surveyed data from professionals.

### References

- Anon., 2009. World Energy Outlook. *International energy agency*.
- Anon., 2012. *MIVAN (Aluminium Formwork)*. [Online] Available at: <http://constructionduniya.blogspot.in/2012/02/mivan-aluminium-formwork.html> [Accessed MAY 2016].
- Anon., 2015. *Compendium of Prospective Emerging Technologies for Mass Housing*, New delhi: Ministry of Housing & Urban Poverty Alleviation, Government of India.
- Anon., n.d. *world carbon-emission analysis*. [Online] Available at: <http://rainforests.mongabay.com/carbon-emissions/> [Accessed April 2016].
- Anon., November 2008 . Briefing Paper | What is a Carbon Footprint?. *Ecometrica Press*.

- Antti Säynäjoki, J. H. S. J., 2011. Carbon Footprint Assessment of a Residential Development Project. *International Journal of Environmental Science and Development*, pp. Vol. 2, No. 2, .
- Bansal, D., Singh, R. & Sawhney, A. R., 2014. Effect of construction materials on embodied energy and cost of buildings. *Energy and Buildings* .
- Barde, A. D., Senou, K., Somaraju, C. K. & Bommi, S., 2014. *NATION'S FIRST HIGH-RISE TOTAL PRECAST CONCRETE RESIDENTIAL BUILDING – STATE OF THE ART OF PRECAST TECHNOLOGY IN INDIA*. s.l.:s.n.
- Chani, P., Najamuddin & Kaushik, S., 2003. *Comparative Analysis of Embodied energy rates for walling elements in India*, s.l.: s.n.
- Das, A. a. S. P., 2014. CO<sub>2</sub> emissions from household consumption in India between 1993–94 and 2006–07: A decomposition analysis. *Energy Economics*, p. 41:90–105.
- Dhaka, S., Mathur, J. & Garg, V., 2012. Combined effect of energy efficiency measures and thermal adaptation on air conditioned building in warm climatic conditions of India. *Energy and Buildings* , p. 55:351–60.
- Jukka Heinonen, A. S. a. S. J. A., n.d. A Longitudinal Study on the Carbon Emissions of a New Residential Development. *University School of Engineering, Finland*.
- Karke, S. M. & Kumathekar, M., n.d. Comparison of the use of Traditional and Modern Formwork Systems.
- Lawson, M., Ogden, R. & Goodier, C., 2014. *Design in Modular Construction*. s.l.:CRC Press.
- Levine, M. D. Ü.-V. K. B. L. G. D. H. S. L. G. L. A. M. M. S. M. A. N. J. R. H. Y., 2007. *Residential and commercial building*, s.l.: s.n.
- Mark Levine (USA), D. Ü.-V. (, n.d. Residential and commercial buildings.
- Markus Weißenbergera, W. J. W. L., March 2014. The convergence of life cycle assessment and nearly zero-energybuildings: The case of Germany. *elsevier*.
- Muthu, S. S., 2016. *The carbon footprint handbook*. s.l.:CRC press.
- Ozawa-Meida, L. B. P. L. K. D. J. a. P. F., 2013. Measuring carbon performance in a UK university through a consumption-based carbon footprint: De Montfort University case study. *Journal of Cleaner Production*, p. 56:185–98.
- Ramachandra, T. a. S., 2012. Decentralised carbon footprint analysis for opting climate change mitigation strategies in India. *Renewable and Sustainable Energy Reviews* , p. 16:5820–33.
- Reiter, S., 07/07/2010. *Life Cycle Assessment of Buildings : a review*. Bruxelles, Belgique, ArcelorMittal International Network in Steel Construction.
- Sartori, I. a. A. H., 2007. Energy use in the life cycle of conventional and low energy building: A review article. *Energy and Buildings* , p. 39:249–57.
- Smith, R. E., 2010. *Prefab Architecture: A guide to modular design and construction*. s.l.:John Wiley & Sons.
- Stripple, H. & Erlandsson, M., May 2004. *Methods and Possibilities for Application of Life Cycle assessment in strategic Environmental Assessment of Transport Infrastructures*, Stockholm, Sweden: IVL Swedish Environmental Research Institute Ltd..
- Talakonukula Ramesh, R. P. K. K. S., n.d. Life Cycle Energy Analysis of a Multifamily Residential House: A Case Study in Indian Context.
- Tiwari, P., 2001. Energy efficiency and building construction in India. *Building and Environment*, p. 36:1127–35.
- Tiwari, P. P. J. a. V. S., 1996. Performance evaluation of cost effective buildings—A cost, emissions and employment point of view. *Building and Environment* , p. 31(1):75–90.
- Wiedmann, T. & Minx, J., June 2007. A Definition of 'Carbon Footprint'. *ISAUK Research & Consulting, United Kingdom*.
- Yakut, A., 2004. *Reinforced concrete frame construction*, s.l.: World Housing Encyclopedia .
- Yin ZHANG, X. Z. , H. Z. G. C. X. W., 2014. Carbon emission analysis of a residential building in Chinathrough life cycle assessment.



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*Design to Thrive*

## Calculation of greenhouse gases in the construction sector in the Aburrá Valley, Colombia

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**Abstract:** The United Nations conferences on Climate Change, COP21 and COP22 renewed the commitment to reduce emissions of greenhouse gases - GHG to the global agenda. Colombia, committed to a 20% decrease in its emissions by 2030 and the construction sector is strategic to achieving this purpose. The aim of this paper is to show the process map and the analysis model built in order to quantify the GHG emissions from building activity in the Aburrá Valley (Antioquia, Colombia), which amounts to 2,3 million m<sup>2</sup>/year. For this purpose, an analysis was made using the Umberto NXT CO2 software for phases 1, 2 and 4 of the life cycle of the building: Phase 1, extraction of raw material, manufacture of building materials and transportation of materials to construction site. Phase 2, construction. Phase 4, transport of Construction and Demolition Waste (CDWs) and disposal/recycling of CDWs. Main construction companies in the region are supplying the data of material consumption and fuel consumption of machines and conveyor vehicles. The expected result of this analysis is the calculation of GHG produced per built square meter from the building activity in the Aburrá Valley, which in turn, will allow identifying mitigation measures.

**Keywords:** Greenhouse Gases (GHG), CO<sub>2</sub> equivalent, life cycle of construction, Umberto NXT CO2.

### Introduction

At present, it is recognized that climate change caused by human activities is one of the greatest environmental challenges that could be placed on the path to sustainable development (Huovila et al., 2007; UNEP et al., 2007; UNEP et al., 2009). Although the construction industry is crucial for global socioeconomic development, the environmental impacts of its processes are increasing significantly.

The life cycle of the construction activity consists of five phases: 1) Extraction of raw materials and manufacture and transportation of materials. 2) Construction. 3) Use or operation. 4) Demolition and final disposal of waste at the end of useful life. 5) Architectural and technical design, where decisions are made that will impact all other phases (see Figure 1).

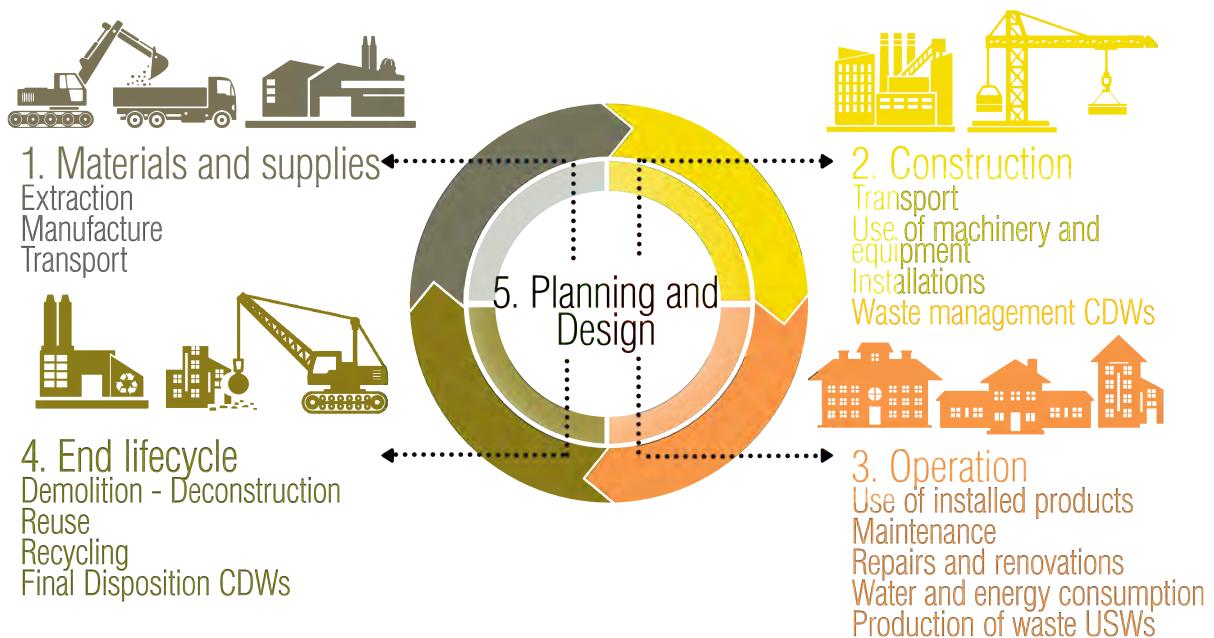


Figure 1. Life cycle of buildings (PVG Arquitectos, 2017).

Recent studies indicate that the construction lifecycle is responsible for 40-50% of GHG emissions worldwide (Abd Rashid et al., 2015). However, this percentage is based on construction activity data in countries with seasonal climates and in developed economies, which are not necessarily valid for tropical countries with emerging economies.

The national inventory of GHG emissions for Colombia allocates 5% to manufacturing and construction industries. However, under a life cycle approach, construction activity is related to other economic sectors, such as transport, responsible for 10% of national emissions, energy industry, responsible for 9%, waste, responsible for 6%, fugitive emissions and industrial processes, each of which is responsible for 4% of national emissions (IDEAM, 2015).

In order to carry out the quantification of emissions in the construction sector, the concept of Carbon Footprint (CF) is introduced, which measures the totality of GHGs emitted by direct or indirect effect of an individual, organization, event or product. The implementation of CF as a methodological tool to measure environmental impact in the construction sector is relatively recent (Abd Rashid et al., 2015; Butera et al., 2015; Cabeza et al., 2014; Chau et al., 2015; Lemay, 2011).

The present study focuses on the implementation and description of a model generated by the software UMBERTO NXT CO<sub>2</sub>, for the quantification of GHG emissions related to phases 1, 2 and 4 of the life cycle of the building activity in the Valley of Aburrá. The stages of extraction, manufacture and transportation of building materials, the construction stage and the transportation and disposal of construction and demolition waste (CDWs) were considered.

## Methodology

For the calculation of the carbon footprint, two basic methodologies, the PAS 2050 Product Carbon Footprint Protocol and the GHG Protocol Product Carbon Footprint, are recognized worldwide. For this study a standard method was used that links both protocols. GHG emissions derived from the operation of buildings are part of a later study and are not part of

the scope of the present study, which focuses only on phases 1, 2 and 4 of the life cycle of the building as described below.

Corresponding processes to phase 1 of the life cycle.

- a) Extraction of raw material and manufacture of building materials.
- b) Transport of materials to construction site.

Corresponding processes to phase 2 of the life cycle.

- c) Construction.

Corresponding processes to phase 4 of the life cycle.

- d) Transportation of CDWs.
- e) Disposal/Recycling of CDWs.

For the phase Extraction of the raw material and manufacturing of building materials, the emission factors were taken from the UNDP, UPME, Ecoingeniería (Jaramillo, 2012) report. In addition, due to the fact that during the construction phase some imported materials, specifically steel, copper and glass were used from the Eco-invent databases (Ecoinvent, 2013) activities associated with the mentioned materials were used to suppose the extraction processes and manufacturing. Material emission factors are reported in kg CO<sub>2</sub> eq/kg, in addition, emission factors reported by the Eco-invent database, in kg CO<sub>2</sub> eq/kg\*km, associated with land and marine transport to Colombian ports of imported materials, were included.

For Transport to construction site and Transport of CDWs phases as well as during Construction Phase for machines that work on site and use fuels (diesel and gasoline) for their use, two different emission factors were used, one associated with indirect emissions and one for direct emissions. For the indirect emissions of fuels associated with the production, transportation, refining and transport of refined fuel, emission factors were taken from official data published by the National Oil Company - ECOPETROL (Martínez-González et al., 2011). For direct emissions, associated to the use of fuels, emission factors presented in the FECOC report were used (Arrieta et al., 2016). In relation to the machines that work in situ but operate with electricity, and for the electrical consumption, the emission factor was taken from UPME's report (UPME, 2015).

Finally, for the phase of disposal and use of waste, emission factors were taken from Eco-invent databases, using as general processes: benefit in a specialized center, waste disposal, landfill disposal and disposal of hazardous waste.

### **Collection and processing of information**

The construction companies that participate in the research are providing the following basic information that has been organized and analyzed by PVG Arquitectos:

- a) The fuel consumption of the dump trucks or transporters, the place of origin and the consumption in tons or m<sup>3</sup> of the different materials used.
- b) Fuel consumption and tons or m<sup>3</sup> of excavation land removed by different machines operating on site.
- c) The fuel consumption of portable mixers, motor pumps and vibrators with tons or m<sup>3</sup> of mixed material, pumped and/or vibrated, either of concrete and/or mortars prepared in factory or on site.
- d) The electric consumption of portable mixers with tons or m<sup>3</sup> of concrete and mortars mixed on site. It also allowed the reporting of total electricity consumption during work and reactive energy measurements.

- e) Water consumption of works.
- f) The different types and quantities of waste identified with the fuel consumption of the transport vehicles and the place of final disposal.

### **Model proposed by UMBERTO NXT CO2 software**

For the calculation of emissions, the Umberto NXT CO2 software was used, for which a process map was designed with a model with 628 variables, in which only one reference flow was used to validate the model. Figure 2 shows the model used, in Sankey diagram form, which allows to observe the mass, volume and energy flows as an increase of the thickness and a color change of the lines. The blue boxes correspond to the different processes of the system, the green circles to entrances to the processes and the red circles to exits. From left to right the analyzed processes were:

- a) Extraction of raw material and manufacture of materials in green.
- b) Transport of materials in yellow.
- c) Construction phase in blue.
- d) Transportation of CDWs in red.
- e) Disposal/recycling of CDWs in violet.

An illustration of the model description is provided in Table 1.

Table 1. Model description.

Phase	Associated processes	Input	Output	Associated emissions
Extraction of raw material and manufacture of materials	T1	V1 to V12		Emissions from materials extraction and manufacture: Steel, imported steel, building ceramics (bricks and roof tiles), decorative and sanitary ceramics, copper, imported copper, stucco, paints, PVC, asbestos cement roof tile, glass and imported glass.
	T3 to T22	V13 to V32		Emissions from materials extraction and manufacture refer to concrete and mortars: Fine aggregates, coarse aggregates, water, river sand, lime and cement.
	T23	V33		Emissions from materials extraction and manufacture refer to total water consumption.
Transport of materials to construction site	T1	P1 to P4		Emissions associated with land and marine transport to Colombian ports of imported materials.
	T2	S1	R1 to R12	The direct and indirect emissions, associated with the fuels (diesel and gasoline) used by material transport vehicles.
	T3 to T22	X1 to X22	R13 to R32	

Construction phase	T3 to T22	X1 to X20	Z1 to Z20	<p>From construction requirements, five concrete classes and five mortar classes were identified, each of which can be prepared either on-site or in a concrete plant. Concrete classes are: slope stabilization; structural; foundations; retaining walls and tanks and structures of environmental engineering. Mortars classes are: structural; gluing; flooring; filler and plaster.</p> <p>Indirect emissions associated with fuels (diesel and gasoline) and electricity. In addition direct emissions associated with fuels (diesel and gasoline). Both direct and indirect emissions are associated with the use of portable mixers, pumping equipment and vibrating machines for concretes and mortars.</p>
	T23	X21		Indirect emissions associated with electrical energy on site, excluding the consumption of processes T3 to T22.
	T24	X22	Z21	Indirect and direct emissions associated with fuels (diesel and gasoline) from excavation and soil adaptation machines.
		X23	Z22	The amount of total excavated soil, the amount of this earth used in the same construction and the amount of excavated ground removed.
	T25			Reference flow for the correct operation of the model. The reference flow includes only the total amount of excavation materials and land (without fuels or electrical consumptions) consumed during construction.
Transportation of CDWs	T24 and T26	U1	Y1 to Y7	The direct and indirect emissions, associated with the fuels (diesel and gasoline) used by the CDWs transport vehicles.
Disposal/Recycling of CDWs	T24 to T26		W1 to W8	Direct emissions generated by the disposal of different wastes, whether they are used in the same construction, are used in a specialized center or by third parties, and if there is a disposition in a slag heap, in landfill or as hazardous waste management.

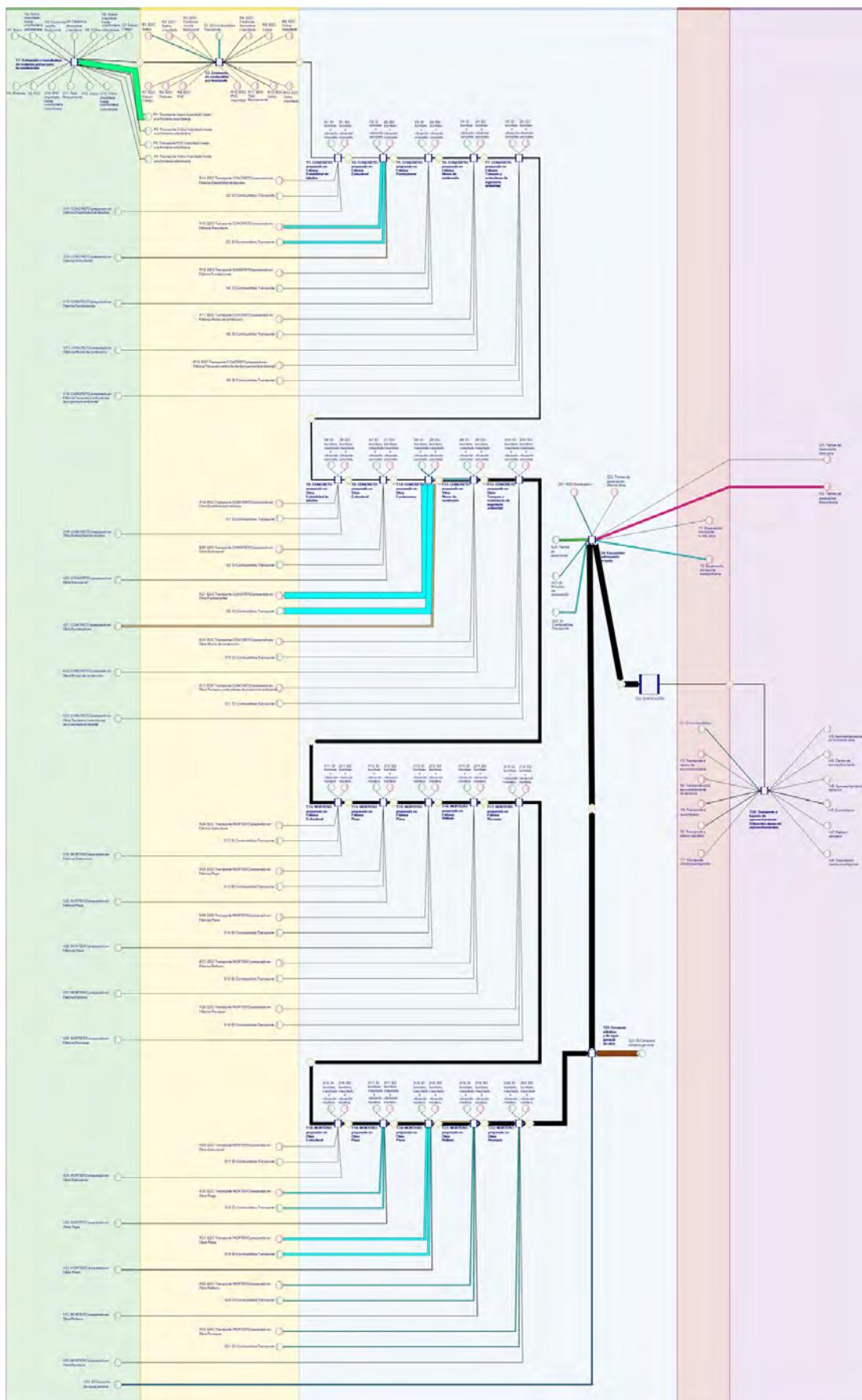


Figure 2. Process map for GHG emissions from building activity using the UMBERTO NXT CO2 software (PVG Arquitectos, 2017).

## Preliminary results

Preliminary results from a first project analysis are shown below. Data correspond to a multifamily housing project of 6850.87 m<sup>2</sup> built area. Figure 2 shows the model in the form of a Sankey diagram for the project analysed and Figure 3 shows the Carbon Footprint with a constructed value of 487.55 kg CO<sub>2</sub> eq/m<sup>2</sup>.



Figure 3. Carbon footprint of a building project in the Aburrá Valley.  
Preliminary results (PVG Arquitectos, 2017).

Figure 4 shows the amounts of kg CO<sub>2</sub>-eq and the percentages corresponding to each of the stages analyzed. The high percentage shown by the phase of extraction and manufacture of raw material and manufacture of materials is mainly due to cement, with a footprint of 1412112.87 kg CO<sub>2</sub>-eq, equivalent to 42.28% and steel, with a footprint of 833118.52 kg CO<sub>2</sub>-eq, equivalent to 24.94%.

Phase	Quantity	Unit	Share
Extraction of raw material and manufacture of building materials	2,811,861.90	kg CO <sub>2</sub> -eq.	84.00
Transport of materials to construction site	409,207.88	kg CO <sub>2</sub> -eq.	12.00
Construction	62,401.82	kg CO <sub>2</sub> -eq.	2.00
Transportation of CDWs	39,148.28	kg CO <sub>2</sub> -eq.	1.00
Disposal/Recycling of CDWs	17,537.12	kg CO <sub>2</sub> -eq.	1.00
	3 340 157.00	kg CO <sub>2</sub> -eq.	

Figure 4. GHG emissions expressed as kg CO<sub>2</sub>-eq and percentages from each analysed stage  
(PVG Arquitectos, 2017).

## Expected results

Expected results from this ongoing study are:

- Calculating GHG per m<sup>2</sup> from building activity in the Aburrá Valley. As mentioned in the introduction of this paper, GHG emission values from building activity that are currently referred, come from countries with developed economies. Therefore this

- study will provide significant information of actual environmental impacts from buildings in tropical countries of emerging economies
- b) Identifying cost-effective mitigation measures useful to comply with the commitment of the building sector to reduce its environmental impacts and implementing criteria of sustainable construction.

Because the construction systems evaluated in this study are widely used in Colombia, the results of this research will not only be useful at the local level, they are also applicable at the national level and may even be a reference for other countries in Latin America.

## References

- Abd Rashid, A. F., Yusoff, S. (2015). A review of life cycle assessment method for building industry, *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 244–248.
- Arrieta, A. A., Janna, F. C., López, D., et al. (2016). *Consultoría técnica para el fortalecimiento y mejora de la base de datos de factores de emisión de los combustibles colombianos-FECOC*, Medellín, Colombia.
- Butera, S., Christensen, T. H., Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management, *Waste Management*, vol. 44, pp. 196–205.
- Cabeza, L. F., Rincon, L., Vilari??o, V., et al. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 394–416.
- Chau, C. K., Leung, T. M., Ng, W. Y. (2015). A review on Life Cycle Assessment , Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings, vol. 143, pp. 395–413.
- Ecoinvent (2013). *Databases Version 3.01*, Zurich, Switzerland.
- Huovila, P., Alla-Juusela, M., Melchert, L., et al. (2007). *Buildings and Climate Change: Status, Challenges and Opportunities*, Sustainable Consumption and Production Branch, Paris, France.
- IDEAM (2015). *Proyecto Informe Bienal de Actualización*, Bogotá, Colombia.
- Jaramillo, A. S. (2012). *Determinación de propiedades físicas y estimación del consumo energético en la producción, de acero, concreto, vidrio, ladrillo y otros materiales, entre ellos los alternativos y otros de uso no tradicional, utilizados en la construcción de edificaciones*, Santiago de Cali, Colombia.
- Lemay, L. (2011). Life Cycle Assessment of Concrete Buildings, In: *National Ready Mixed Concrete Association (NRMCA)*, pp. 1–12, Maryland, United States.
- Martínez-González, A., Casas-Leuro, O. M., Acero-Reyes, J. R., et al. (2011). Comparison of potential environmental impacts on the production and use of high and low sulfur regular diesel by life cycle assessment, *CTyF - Ciencia, Tecnología y Futuro*, vol. 4, no. 4, pp. 123–136.
- PVG Arquitectos (2017). *Elaboración Propia*, Medellín, Colombia.
- UNEP, SBCI (2007). *Assessment of Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings*, United Nation Enviroment Programme and Central European University, Paris, France.
- UNEP, SBCI (2009). *Buildings and Climate Change: Summary for Decision Makers*, United Nation Enviroment Programme and Central European University, Paris, France.
- UPME (2015). *Informe Mensual de Variables de Generación y del Mercado Eléctrico Colombiano-Diciembre de 2015*, Medellín, Colombia.



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## Addressing Embodied Carbon in High Performance Design

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**Abstract:** Design professionals are focusing on driving down building operational energy consumption as a way to address climate change and the built environment. Passive house is one approach to high performance design using super insulation, airtight construction, and high performance windows. Operational energy savings in passive houses are anticipated to be 70% better than code. We wondered how the embodied energy (energy used in material manufacturing and construction) of passive houses compares to the carbon emissions from operating these high performance buildings. This paper compares the embodied energy and carbon emissions of a multifamily, affordable passive house building and a similar building of standard construction – the Stellar Apartments (first certified, affordable multi-family passive house in the US, completed in August 2013). The passive house (PH) building has undergone continuous energy monitoring alongside a building of identical layout but built to an optional Oregon state energy standard, Earth Advantage (EA) which is estimated to be 10-15% better than code. Revit, Zero Tool, and Tally® will be used to calculate and compare the environmental impacts of the materials and operation in these buildings. Alternative wall assemblies will also be examined to evaluate the feasibility of achieving truly zero carbon buildings.

**Keywords:** embodied carbon, passive house, Stellar Apartments, Tally®, Zero Tool

### Introduction

The Paris Climate Agreement commits the international community to keeping “global average temperature increase well below 2°C above pre-industrial levels” while pursuing efforts to limit the temperature increase to 1.5°C. The Intergovernmental Panel on Climate Change (IPCC) estimates that in order to achieve this goal, the world must phase out fossil fuel CO<sub>2</sub> emissions by 2050 (IPCC, 2013) (Hare et al., 2014). Global companies, foundations, and leaders in all sectors are responding to this call and establishing practical steps and commitments to reach this goal. According to Architecture 2030, between 2015 and 2050 more than two trillion ft<sup>2</sup> (192 billion m<sup>2</sup>) of building stock will be constructed, retrofitted, or torn-down and reconstructed worldwide – equivalent to building an entire New York City (all five boroughs) every 35 days for 35 years (IEA, 2016). It is crucial that we design and construct this building stock to Zero Net Carbon standards by 2050 if we hope to meet the global goal set by the Paris Climate Agreement. This goal can only be reached if building design addresses both operational and embodied carbon emissions.

Examining the lifespan (assumed 60-years) of a building built to current code standards, embodied energy represents about 45% of the building’s total energy footprint, while operational energy represents the remaining 55% (Architecture 2030).

However, as buildings become more efficient and operational energy consumption is reduced, the relative impact of the embodied carbon of materials increases. Furthermore, to reach Zero Net Carbon by 2050, there are only 33 years left to eliminate building sector carbon emissions. For the approximately two billion ft<sup>2</sup> (192 billion m<sup>2</sup>) that we'll construct globally in that time, Architecture 2030 estimates that as much as 90% of the energy footprint of that building stock (when energy footprint estimates are cut off at 2050) will be embodied energy, emphasizing the crucial role that embodied carbon reductions must play in achieving global climate goals (Architecture 2030).

This study focuses on the relationship between the embodied carbon of materials and the operational carbon emissions of buildings designed to passive house standards. Passive house buildings are estimated to reduce operational energy consumption by 70%, using super insulation, airtight construction, constant fresh air ventilation, and high performance windows. However, we see multiple examples of very high-embodied carbon materials used to insulate these very low energy consumption buildings. Given our global carbon deadline, material choices play a much more significant role. If the embodied carbon of building materials exceed the operational energy savings, the effort to achieve a high performance building becomes futile.

### ***Research Objectives***

This study offers a quantitate analysis of both the embodied carbon of materials and the carbon emissions from operational energy consumption in the Stellar Apartments: comparing a passive house (PH) building with an identical in layout building built to an optional State energy code, Earth Advantage (EA) (estimated to be approximately 10-15% better than code). The Stellar Apartments passive house building was the first affordable, multi-family apartment complex to achieve PHIUS certification in the United States, built in 2013 in Eugene, Oregon by the Saint Vincent de Paul Society of Lane County. The following objectives will test assumptions about material choices when designing high-performance buildings:

- Calculate the embodied carbon of the materials of the PH and EA buildings to determine if the PH building is more carbon intensive than the EA building, and if so, by how much;
- Compare the embodied carbon results of the PH and EA buildings to their operational energy use intensity (EUI) to see if the operational energy performance is worth the embodied carbon investment;
- Using those results, identify and analyse alternative wall assemblies to explore the feasibility of designing zero-carbon buildings.

### ***Methods and Approach***

*Buildings:* The Stellar PH and EA buildings are identical in their layout and orientation but differ in their wall assembly, windows, ventilation, and shading. Both buildings have a 2x6" (51x152 mm) stud wall with blown in cellulose insulation, use cement-fiber board siding, asphalt shingled roofs, and the same interior finishes. However, the PH building has an additional 4 inches (102 mm) of polyisocyanurate (polyiso) insulation outboard of the studs, and has high- performance windows. The PH building uses triple pane, argon-filled casement windows and the EA has double pane double-hung windows. Beginning in 2013 the two buildings underwent a two-year energy-monitoring case study.

The operational energy consumption data from that case study will be used in the following calculations and comparisons.

*Carbon emissions from operational energy:* The operational energy consumption of the PH and EA buildings were calculated. This data will be run through Architecture 2030's Zero Tool to estimate and compare the operational greenhouse gas (GHG) emissions of the PH and EA buildings. This step converts energy consumption into carbon emissions. The Zero Tool uses EPA Target Finder data and methodology to calculate energy baselines normalized by climate, weather, space type, building size, occupancy, and schedule, and estimates operational GHG emissions.

*Embodied carbon from building materials:* Tally®, a software plug-in for Revit, will be used to quantify the embodied carbon impacts of the building materials. The analysis will be run for both the PH and EA buildings and will be compared to their operational carbon emissions. Though Tally® provides a robust number of environmental impact measurements, this analysis will focus primarily on Global Warming Potential (GWP). Note that the Tally-provided averages were used to estimate transportation and construction emissions for two reasons: First, to make the results of this study more universally applicable instead of site-specific, and second, it was not possible to track down the exact material manufacturer for every material used in the apartment buildings. However, when used in architectural design projects, specifying project- specific data instead of using Tally® averages will result in more accurate calculations, allowing for better decision-making.

*Embodied carbon of alternative building materials:* This study will also examine alternative material choices, comparing four wall assemblies to see how lower embodied carbon materials impact the total GHG emissions (embodied and operational) of the PH building and analyzing the balance of embodied and operational carbon on the path towards zero-carbon construction.

## Results

The Stellar Apartments PH building has an average site EUI of 16.3 kBtu/ft<sup>2</sup>/year (49.6 kWh/m<sup>2</sup>/yr). The Stellar EA building's EUI was 25.6 kBtu/ft<sup>2</sup>/year (77.7 kWh/m<sup>2</sup>/yr). Throughout the two-year energy monitoring case study, it was found that the PH building performed 38% better than the EA building (NetZED Laboratory, 2016). These values were used in the Zero Tool to estimate the correlating GHG emissions from operational energy consumption.

Table 1. Emissions impacts of Stellar PH and EA; GSF = 6,156 ft<sup>2</sup> (571.9 m<sup>2</sup>)

	Annual Operational GHG emissions (metric tons CO <sub>2</sub> e)	Total Operational GHG emissions assuming 60 year lifespan (metric tons CO <sub>2</sub> e)	Estimated Total GWP (metric tons CO <sub>2</sub> e)	Operational Payback for Embodied (years)	Total E+O emissions, assuming 37 years, or 2013 to 2050 (metric tons CO <sub>2</sub> e)	Total E+O emission, assuming 60 years (metric tons CO <sub>2</sub> e)
Stellar PH	12	720	245.5	2.9	605.5	965.5
Stellar EA	18	1080	208.1	5.2	748.1	1288.1

### **Payback Time Analysis**

Tally® results show that the Stellar passive house building has an estimated GWP of 245,532 kgCO<sub>2</sub>e, or 245.5 metric tons CO<sub>2</sub>e. The Earth Advantage building has a GWP of 208,077 kgCO<sub>2</sub>e, or 208.1 metric tons CO<sub>2</sub>e [Table 1]. This means that the added four inches (102 mm) of polyiso insulation and the high-performance windows added 37,455 kgCO<sub>2</sub>e (37.5 metric tons CO<sub>2</sub>e).

From the Zero Tool, we calculated that the annual operational GHG emissions for the PH building were 12 metric tons CO<sub>2</sub>e and 18 metric tons CO<sub>2</sub>e for the EA building. To calculate total embodied and operational carbon emissions, we multiply annual GHG emissions by the assumed life span (assumed 60 years) for total operational GHG emissions and add that to embodied carbon value. For the PH and EA buildings, the total emissions are 965.5 and 1288.1 metric tons CO<sub>2</sub>e, respectively. However, taking into account the goal of Zero by 2050, we would be looking at the time span between construction and 2050; in this case, that is 37 years. Therefore, the total emissions would be 605.5 and 748.1 metric tons CO<sub>2</sub>e, respectively.

These results show that even though the embodied carbon in the PH building is higher due to the additional insulation, the payback time was actually lower than the EA building due to the operational energy performance. Additionally, for both the time span to 2050 and the life of the building, PH has a lower total combined emissions than the EA building. The results from this research shows one great approach to designing zero carbon buildings is to follow passive house standards for operational energy performance (higher insulation values, airtightness, fresh air ventilation, and high performance windows) and then to greatly reduce embodied carbon of the materials chosen through comparative analysis. The following attempts to do just that.

### **Key GWP contributors**

The Tally® results show that the six highest GWP contributors for the Stellar PH building were: polyiso insulation (17%); asphalt singles (13%); gypsum board (13%); wood framing with insulation (13%) [blown-in cellulose with kiln-dried softwood framing]; plywood (7%); and carpet (5%) [Figure 1]. These seven categories alone contributed 68% of the overall GWP, or roughly 166,961 kgCO<sub>2</sub>e.

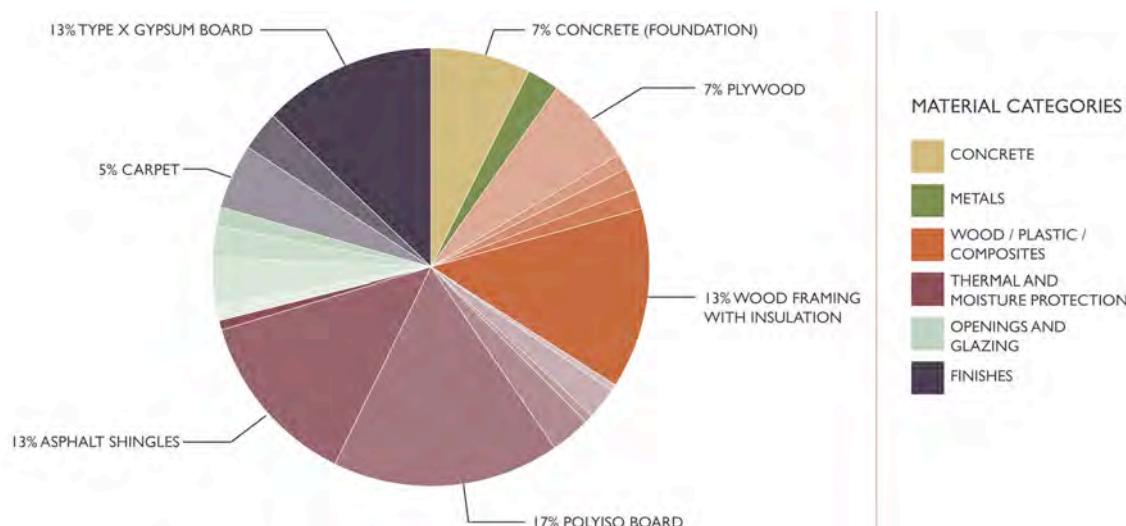


Figure 1: Embodied Carbon break-down of the as-built Stellar PH building

Polyiso has the highest R-value per inch of any insulative material resulting in the greatest operational energy savings, but was also the largest contributor of embodied carbon to the Stellar PH. This highlights the importance of understanding the embodied carbon impacts of material choices and balancing that with their relative operational savings.

### ***Alternative Wall Assembly Comparison***

This analysis compares four wall assemblies of equal R-value to quantify and understand the opportunities for lower embodied carbon in buildings. Each wall assembly was designed to have the same R-value as the as-built PH wall, R-48, so that operational performance would remain relatively constant. The Stellar PH wall assembly was compared with a SIPS panel wall assembly with EPS, a double stud wall assembly, and a ModCell® straw panel system [Figure 2].

These wall assemblies were chosen to represent the (assumed) extremes of embodied carbon. It was predicted that even with EPS instead of XPS, SIPS panels would have the most embodied carbon, followed by the Stellar PH wall assembly, the doubled stud wall assembly, and then Straw Panels with the lowest embodied carbon.

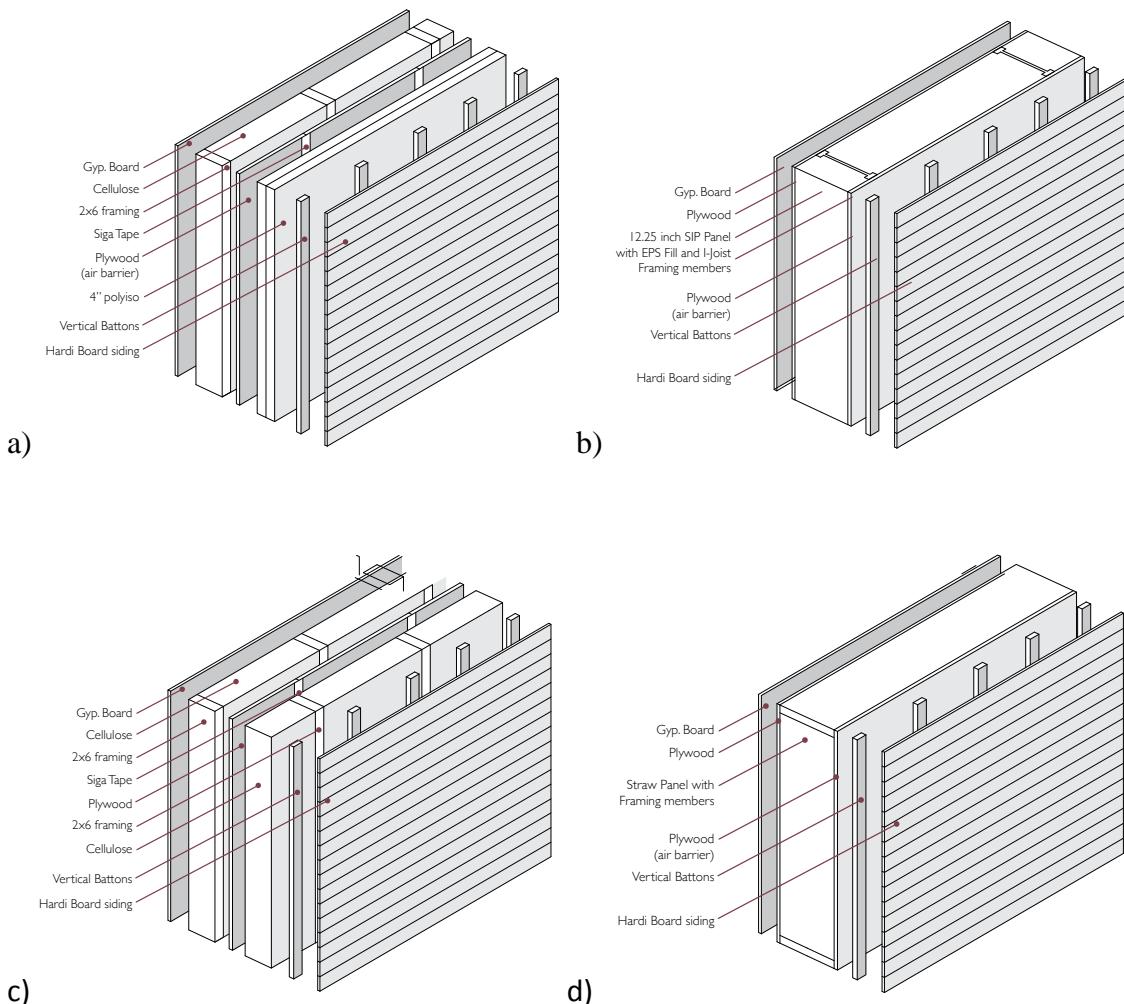


Figure 2. Four wall assemblies compared: a) Stellar PH; b) SIPS; c) double stud; and d) ModCell straw panel system.

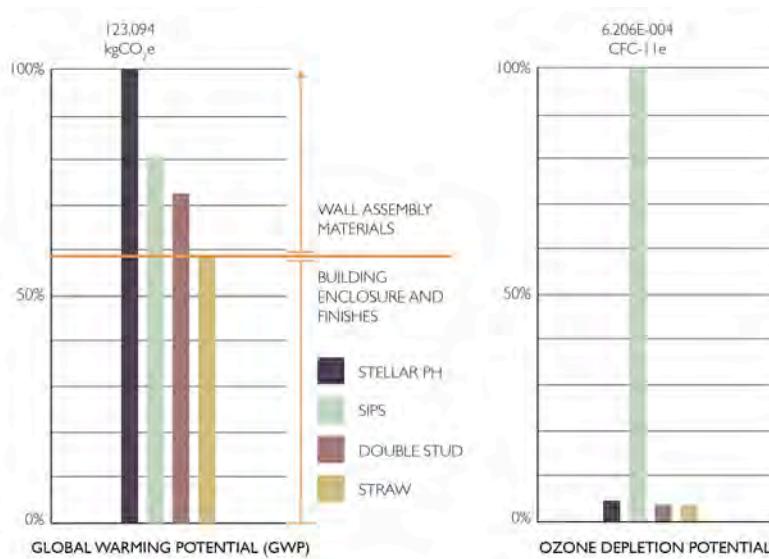


Figure 3. Wall assembly comparison: GWP (left) comparison shows the embodied carbon of the building enclosure and finish materials (interior walls, floors, and roofing) and the additional embodied carbon of the compared wall assembly materials. The ODP (right) comparison shows the impact of SIPs due to the harmful blowing agent, HCFCs.

The results both proved and disproved our assumptions. As illustrated in Figure 3, the embodied carbon of the Stellar PH wall assembly greatly exceeded the other wall assemblies, which was not predicted. Additionally, the SIPS panel was relatively close to the double stud wall assembly, also unexpected. It should be noted, though, that the Ozone Depletion Potential of the SIPS panels greatly exceeded all other wall assemblies [Figure 3, right], showing that the hydrochlorofluorocarbons (HCFC's) in the blowing agent for EPS insulation has the greatest impact on the climate, though results in ozone depletion rather than global warming. The double stud wall is shown to have a relatively high GWP, which contradicts our assumptions and previous research. The GWP result for cellulose was much higher than expected. The Environmental Product Declaration (EPD) used by Tally® showed an embodied carbon of 32.19

kgCO<sub>2</sub>e per m<sup>3</sup> for cellulose, but was only valid until 2014. A second EPD, issued in 2014 and valid until 2019, found that when adding the production phase (which was carbon negative) to the disposal phase (more carbon intensive), the total embodied carbon ranged from 4.89 to

11.61 kgCO<sub>2</sub>e per m<sup>3</sup> for cellulose for densities of 28 kg/m<sup>3</sup> and 65 kg/m<sup>3</sup>, respectively (Bau EPD,

2014). This newer information might explain why the GWP for the Stellar PH wall and the double stud wall was higher than expected.

Tally® does not have straw in its material database, so data for the straw panel came from ModCell (a U.K. based straw panel manufacturer). ModCell straw panels are 3 x 3.2 m (roughly 9'10" x 10'6") panels which each hold 1300 kg CO<sub>2</sub> of sequestered carbon. However, materials such as straw and wood that sequester carbon can actually be considered carbon neutral since they release their stored carbon at the end of their life. Manufacturing emissions are not included in this value.

## **Future Steps**

With each variation in the materials choice, the thermal performance of the building will likely vary and therefore new operational energy assessments are necessary, using predictive modeling. Additionally when comparing wall assemblies with the goal of reducing the embodied carbon of the building design, the next step would be to determine vapor drives in each wall assembly to verify that it would perform as intended in the specific climate zone.

## **Conclusions**

Using Tally®, we were able to quantify the embodied carbon impacts of the first affordable, multi-family passive house in the U.S., the Stellar Apartments. The results show that even though the PH building had a longer payback period when comparing embodied carbon to operational GHG emissions, the total emissions for the PH building are significantly lower than the EA building both in the lifespan of the building and to a deadline of 2050. This shows that one feasible pathway to design zero carbon buildings is using passive house standards to greatly reduce operational carbon emissions, and then focusing on using low embodied carbon materials to further drive down total carbon emissions.

When specifying low embodied carbon materials, it is important to identify the materials with the largest embodied carbon values and to consider lower-embodied carbon alternatives. This also opens the conversation about alternative material choices. Gypsum board, for example, is the predominant interior wall finish used in U.S. construction today, yet it is one of the highest contributors to total embodied carbon. In designing low embodied carbon building, alternative interior finishes should be investigated and used.

It is important to compare materials by both the embodied value and the lifespan of the material. Two materials may have similar kgCO<sub>2</sub>e/kilogram values, but it makes a significant difference if one has a lifetime of 15 years and the other has a lifetime of 60 years. In this case, the asphalt shingles contribute considerably to the overall embodied carbon of the building partly due to their short life-span (15 years) requires multiple replacements (and thus additional embodied carbon emissions) over the lifespan of the building.

Comparing manufactured materials to natural, carbon-neutral materials is complex and it is critical to define a time span when evaluating embodied carbon impacts. For example,

cellulose (recycled paper) sequesters carbon and has an initial carbon negative value, but when sequestered carbon is released at end-of-life, the material does have a significant carbon impact. That said, materials that sequester carbon can never release more than what they initially sequester (not accounting for manufacturing, transportation, and disposal emissions), and are inherently carbon-neutral. This study did a whole life cycle (cradle to grave) analysis, showing the full lifecycle of carbon emissions and not just the upfront carbon emitted or sequestered. However, when the timeframe is shortened from the life of the building (assumed 60 years) to the threshold set by the Paris Agreement of Zero by 2050, using materials that sequester carbon up-front is key to reaching the goal of Zero by 2050.

If we hope to meet the goal set by the Paris Agreement of Zero Net Carbon by 2050, the embodied carbon and material choices becomes significant. There are many factors

involved in deciding which material to use in a wall assembly; and it is important to examine energy *and* an embodied carbon as in iterative process throughout all phases of design. Tools such as Tally® make this much more feasible and get us closer to reaching Zero by 2050.

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### References

- Architecture2030. <http://architecture2030.org/>
- Bau-EPD (2014). *Blown insulation made of cellulose fibre*. [online] Available at: [http://www.bau-epd.at/wp-content/uploads/2014/11/EPD\\_ISOCCELL\\_Ecoinvent\\_20140825-English.pdf](http://www.bau-epd.at/wp-content/uploads/2014/11/EPD_ISOCCELL_Ecoinvent_20140825-English.pdf) [Accessed 16 Mar. 2017].
- Hare, B. et al. (2014). *Is it possible to return warming to below 1.5°C within this century?* [online] Climate Analytics. Available at: [http://climateanalytics.org/files/climate\\_analytics\\_briefing\\_is\\_it\\_possible\\_to\\_return\\_warming\\_to\\_below\\_1\\_5degc\\_within\\_this\\_century-.pdf](http://climateanalytics.org/files/climate_analytics_briefing_is_it_possible_to_return_warming_to_below_1_5degc_within_this_century-.pdf) [Accessed 01 Jan. 2017].
- IEA. (2016), *Energy Technology Perspectives 2016*. [online]. International Energy Agency. Available at: [https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2016\\_ExecutiveSummary\\_EnglishVersion.pdf](https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2016_ExecutiveSummary_EnglishVersion.pdf) [Accessed 02 Jan. 2017].
- IPCC AR5 WG1 (2013). *Climate Change 2013: The Physical Science Basis. Working Group 1 (WG1) Contribution to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5)*. [online] IPCC. Available at: [https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5\\_SPM\\_brochure\\_en.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WGIAR5_SPM_brochure_en.pdf)
- ModCell Straw Panel: strawbale panel manufacturer based in Bristol, England. <http://www.modcell.com/>
- Moore, Erin and B. Waldman. (2014). Time, Material, Environment: A Life Cycle Assessment Model for Calculating Greenhouse Gas Payback Time for Building System Upgrades. *Sustainable Structures Symposium*. Portland State University, OR. April 16-17
- NetZED Laboratory, (2016). *Stellar Apartments: The Story and Data Behind the Nation's First Affordable Multifamily Passive House*. 86 pp. <http://www.lulu.com>
- Tally® life cycle assessment software: developed by architecture firm KierenTimberlake, uses material quantities from Revit and embodied carbon data from a life GaBi database to estimate embodied energy.

# Comfort & Delight

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## Indoor Thermal Comfort for Residential Buildings in the Hot-Humid Climate of Nigeria during the dry season

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**Abstract:** The indoor thermal conditions in residential buildings in two locations in Abuja, Nigeria were investigated to understand the ideal conditions of occupants in this hot-humid climate. Understanding these conditions helps give an insight into what people are experiencing in their houses and how they adapt to the high temperatures. The study seeks to fill the gap in research of occupants' thermal comfort in this area by providing empirical thermal comfort data from a city in the tropical region. During the study, 86 households responded to a post occupancy questionnaire to evaluate their building and how they adapt to high temperatures. A comfort survey questionnaire was administered to occupants of four low-income residential households to assess their perception of their thermal environment. These included two air conditioned and two naturally ventilated buildings with the questionnaires having over 80% return rate. Simultaneously, physical measurements were taken in the living room, bedroom and outdoor spaces to evaluate the actual building performance and thermal environment. Most occupants in the residential buildings in this climate experienced thermal discomfort and were uncomfortable with their thermal environment as suggested by the results of the study. The data further suggest the preferred conditions are operative temperatures above 28°C.

**Keywords:** Thermal comfort, Residential buildings, hot-humid Climate

### Introduction

The current high indoor temperatures experienced in residential buildings, especially those in the big cities like Abuja in Nigeria are thermally uncomfortable for a substantial period (Adunola and Ajibola, 2012). Unfortunately, the housing condition in the country is of extreme worry as it is largely of poor quality and standard in both rural and urban centres. The increase in the quantity of housing needed has led to a major and evident concern about the quick deterioration of the current housing stock leading to a shortage of housing units (Olayiwola et al., 2005). Hence, because of the rush to meet demand, builders tend to focus more on quantity rather than quality therefore compromising standards and indoor comfort. Most occupants now rely on mechanical cooling: mostly, fans and air conditioning, to achieve thermal comfort.

Mechanical cooling is largely dependent on electricity in Nigeria of which the residential buildings sector consumed 53.3% of electricity generated as seen in the Federal Government of Nigeria's 2009 vision 2020 report in (Oyedepo, 2014); (Adaji et al, 2015). However, due to the lack of a reliable and continuous power supply from the national grid, mechanical cooling systems in residential buildings are not dependable to provide cooling. Also, these cooling mechanisms (like air conditioning) require lots of energy to run and maintain. Hence, relying on the continuous running of air conditioning is not feasible and sustainable (Adaji et al,

2015). In addition to the lack of a constant power supply, people frequently turn to generators as a back-up power supply for their electrical appliances especially for mechanical cooling.

A thermal comfort study was carried out in Abuja, with a view to understanding the conditions of residents in buildings across two different residential neighbourhoods in the city, during the dry season. This paper tries to understand the ideal and preferred conditions of thermal comfort in low-income buildings in Abuja, Nigeria. Furthermore, monitoring of air temperatures and humidity was carried out to determine the maximum, minimum, average values and the way people adjust to achieve thermal comfort in buildings located in this area to understand what residents are experiencing. Studies such as this could also assist the improvement and recommendations of diverse levels of tropical comfort considerations required in the standards (Djongyang et al. 2010).

### ***Study area and case study description***

The study area Abuja, lies at latitude 9° 07' N and longitude 7° 48' E, at an elevation of 840 m (2760 ft.) above sea-level. The area now designated the Federal Capital Territory (F.C.T.), Abuja, Nigeria's capital, falls within the Savannah Zone vegetation of the West African sub region with Patches of rain forest. As it is in the tropics Abuja experiences two weather conditions annually; the rainy season ranging from 305 to 762 mm (12–30 in.) which begins in April and ends in October and the dry season (the equivalent of summer in a temperate climate) which begins in November and ends in March, but within this period, there is a brief interlude of Harmattan, a period when the North-East Trade Wind moves in with the main feature of dust haze, intensified coolness and dryness. Fortunately, the high altitudes and undulating terrain of the FCT act as a moderating influence on the weather of the territory. Temperatures can rise to 40°C during the dry season with dry winds lowering the temperature to as low as 12°C (Abubakar, 2014).

Four case studies in two locations (Lugbe and Dutse Alhaji) in Abuja were identified to investigate the thermal comfort of occupants with their means of ventilation (natural ventilation and air conditioning), purpose of construction (for low income group) and building type (low rise building) as the main selection criteria.



Figure 1: Floor plan of the Case Study 1 (left) and Case study 2 (right) in Lugbe, Abuja.

Case study 1, Lugbe (LGH1) (see figure 1), is in a low-middle income area (though designated a low-income area) called Light Gold Estate just off the express way linking the international airport in Abuja to the city centre. It's a 3-bedroom, north facing detached bungalow, built with sandcrete blocks, has aluminium roofing with no insulation and is naturally ventilated.

Case study 2, Lugbe (LGH2) (see figure 1), is in a low-middle income area in Lugbe and is in the same location as the first house only not in the same estate but north of the first case study, called Trade Moore Estate. It's an air conditioned north east (East by North) facing, 2-bedroom north facing semi-detached bungalow, built with sandcrete blocks and has aluminium roofing with no insulation.

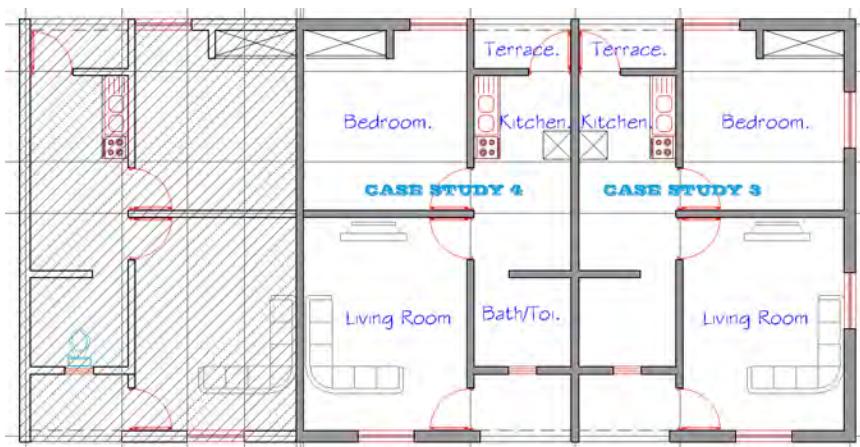


Figure 2: Floor plan for Case study 3 and 4 in Dutse Alhaji, Abuja

Case study 3 (DAH1) (see figure 2), in Dutse Alhaji, is in a low-income, high density area. The building is naturally ventilated and has a painted exterior. It is roofed with iron sheets with no insulation. Finally, Case study 4 (DAH2) is in the same area and is a 1 bedroom air conditioned flat attached to DAH1 (see figure 2).

#### *Research methods and techniques used for this research*

The methodology for the survey included environmental monitoring, post-occupancy and comfort surveys. These surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation within the buildings and occupant's energy demands and use. The Post-occupancy studies are basic to evaluating the thermal condition in buildings, while the comfort surveys help to understand and in addition analyse the nature and occurrence of occupants' complaints of experiencing warmth or feeling hot through the day that can't be acquired during thermal investigations (Nicol and Roaf, 2005); (Adekunle and Nikolopoulou, 2014).

**Post-occupancy survey:** This survey focused on dwellings other than the case study buildings but situated in the same areas. They add breadth and support the results from the individual case studies. Each questionnaire in the current study has 31 questions, divided into three main sections: Section A, includes background information about their location, gender, age, socio-economic status, educational and occupancy status; Section B, asks about building attributes and energy consumption including house type, number of rooms in the building and duration of occupancy; Section C, considers indoor thermal conditions and looks at how residents make themselves comfortable by opening and closing windows or doors, and

clothing type. Overall 100 questionnaires were distributed, 90 (90%) were returned and of these 86 (86%) were correctly completed. All the questionnaires were self-administered.

*Comfort survey:* Thermal comfort questionnaires were issued to the occupants of the dwellings monitored. They were asked to complete the questionnaires three times per day to assess their thermal comfort state, (using the seven-point ASHRAE thermal sensation scale and a five-point preference scale). Further information on clothing insulation and activity was also collected. The comfort survey was designed as a daily diary evaluating occupants' responses to discomfort and how they achieve comfort at various times of the day (morning, afternoon and evening) for a week. These data were used to support the physical data collected at the same time.

*Environmental Monitoring:* The field survey was conducted during the dry season from 11/03/15 to 18/04/15. Air temperature and relative humidity were recorded using HOBO Temperature and Relative Humidity sensors installed on the internal walls at a height of 1.1m above the ground floor level. Four dwellings were monitored in Abuja, with two spaces representing the living room area and bedroom area monitored in each case study. The outdoor environmental conditions measured were air temperature and relative humidity using Tiny Tag T/RH sensors inside a radiation shield and global solar radiation on the horizontal. Data was recorded every 15 minutes.

### **Data analysis**

#### *Analysis of Post-Occupancy Survey:*

Lugbe had 43 questionnaires returned, of which 26 (60.5%) were from male and 17 from female (39.5%). Dutse Alhaji had 43 questionnaires returned with 33 (76.7%) male and 10 (23.3%) female responses.

The warm part of the scale in the dry season, had a much greater response across all the respondents of the case studies, with 74.4% of occupants feeling 'warm' or 'hot' at Lugbe and 86.1% at Dutse Alhaji. The mean thermal sensations for Lugbe and Dutse Alhaji (Table 1) in the dry season were around the 'slightly warm'. The overall thermal sensation results across the two case studies show that 80.2% felt either 'warm' or 'hot' during the dry season.

The thermal satisfaction was measured on a 7-point scale with 1 for very dissatisfied to 7 for very satisfied. In Lugbe, 37.2% were satisfied with their thermal environment compared to 90% of respondents of Dutse Alhaji that were either 'very dissatisfied', 'dissatisfied' or 'slightly dissatisfied'.

Table 1: Post occupancy survey mean responses for the overall thermal sensation, thermal satisfaction, overall thermal comfort in the dry season

Case study	Overall Thermal sensation	Thermal satisfaction	Overall thermal comfort
Lugbe	5.8	3.9	3.6
Dutse Alhaji	6.0	2.1	5.3

A 7-point scale (from 1 for very uncomfortable to 7 for very comfortable) was used for the overall thermal comfort. There was an almost even distribution of the comfort votes in

Lugbe where 49.5% were dissatisfied, i.e. only slightly skewed towards discomfort. However, 81% of the respondents in Dutse Alhaji indicated they were uncomfortable with their thermal environment. These results suggest that the thermal environment has been influenced by the air conditioning in these buildings, as houses in Lugbe have more air conditioning compared to those in Dutse Alhaji.

*Analysis of Comfort Survey:*

105 questionnaires were administered during the dry season and 71 were received (67.6% response), while 105 were administered during the rainy season and 55 were received, (52.4% response).

The comfort surveys show most of the occupants were feeling warm with most of the distribution of votes varying from 'slightly' warm' to 'hot'. The results suggest that 50% of the time the occupants in Lugbe LGH1 felt 'warm' while 25% of the time occupants in Lugbe LGH2 felt 'warm'. Also, 76.9% of the time the occupants in Dutse Alhaji DAH1 felt 'warm' compared to 25% of the time in Dutse Alhaji DAH2. The 25% warm votes recorded in Lugbe LGH2 and Dutse Alhaji DAH2 can be attributed to the use of air conditioning in these dwellings, though the 'slightly warm' votes in Lugbe LGH2 and Dutse Alhaji DAH2 were 53.6 and 56%.

Most of the residents spent 12 hours inside the house per day and most of the participants from the survey had lived in the case study buildings for over 36 months. The residents in Lugbe owned the properties they live in while the occupants in Dutse Alhaji lived in rented buildings. More than 70% of the spaces monitored in all case studies recorded temperatures above the comfort range.

Table 2: Thermal comfort survey mean responses for the thermal sensation in the dry season

Case study	Overall Thermal sensation
Lugbe (LGH1)	5.4
Lugbe (LGH2)	5.0
Dutse Alhaji (DAH1)	5.8
Dutse Alhaji (DAH2)	5.0

The thermal sensation analysis shows a distribution clustered above the central categories with more than two-thirds of the responses feeling 'uncomfortably warm' with a moderately even distribution of votes varying between 'neutral' and 'warm' (See table 2).

Linear regression analysis was used to calculate neutral and preferred temperatures (See Figure 3), which were in a range of 28°C to 30°C. This showed that occupants in this region of Abuja have a potential to adapt to high temperatures. Occupants in Lugbe showed more adaptation potential, with a higher neutral temperature of 29.6°C and preferred temperature of 28.3°C, compared to a neutral temperature of 28.2°C and a lower preferred temperature of 25.4°C in Dutse Alhaji.

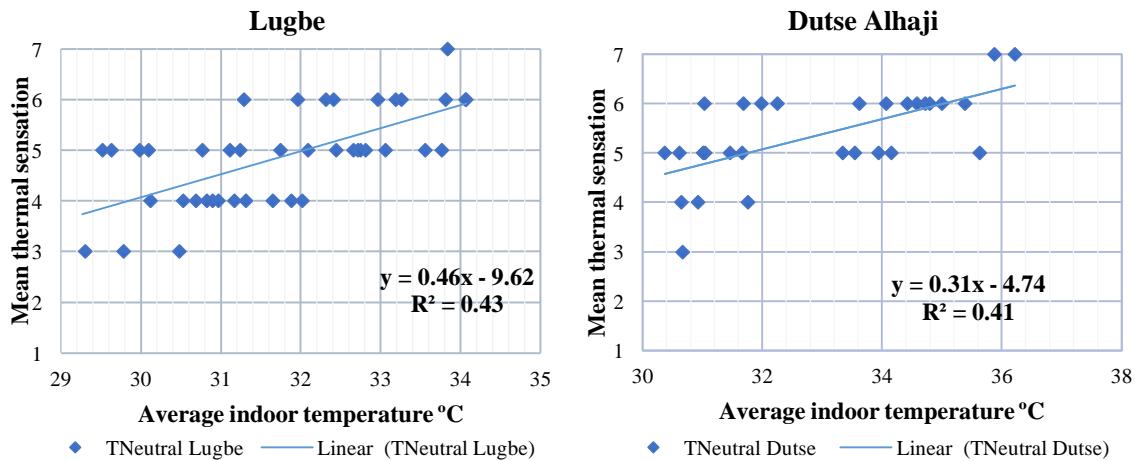


Figure 3: Relationship between the thermal sensation and the average indoor temperature at Lugbe (left) and Dutse Alhaji (right) during the dry season

#### *Analysis of Environmental Survey:*

The outdoor temperature recorded in Lugbe during the dry season varied from 23.5°C on 21/3 to a maximum of 41.1°C on 19/3, with a relative humidity varying from 19% on 19/3 to a maximum of 91% on 21/3, and an average of 56%; while the outdoor temperature in Dutse Alhaji varied from 23.0°C on 15/4 to a maximum of 38.4°C on 14/4, with a relative humidity varying from 10% on 17/4 to a maximum of 93% on 11/4 and an average of 37% throughout the monitoring period.

The measured outdoor temperature had a running mean temperature,  $T_{rm}$ , as defined by BSENI 15251 (BSI, 2008), varying from 32.1°C on 23/3 to a maximum of 33.3°C on 21/3 in Lugbe and 30.8°C on 11/4 and a maximum of 31.4°C on 17/4 in Dutse Alhaji during the dry season monitoring. The results suggest that Lugbe had the hottest month of the year (March), with an average indoor temperature of 32°C and a maximum outdoor temperature of 41.1°C.

The average indoor temperature between 08.00 and 22.00 in the monitored living areas in Lugbe was 32°C for the living rooms and 32°C for the bedrooms. The living room space recorded the hottest temperature in the building with a mean of 32.5°C and a maximum temperature of 36.2°C. The average temperature between 23.00 and 07.00 was 31.3°C for the living rooms and 31°C for the bedrooms. The living rooms were also the hottest space in the building with a mean temperature of 31.1°C and a maximum temperature of 34.6°C. There is a positive relationship between the indoor and outdoor temperatures and the living room temperatures in the two case studies are much higher and warmer than the bedroom spaces because of their higher occupancy throughout the day.

In Dutse Alhaji, the average temperature between 08.00 and 22.00 in the monitored living areas was 34.4°C for the living rooms and 31.1°C for the bedrooms. The living room space recorded the hottest temperature in the building with a mean of 34.5°C and a maximum temperature of 36.8°C. The average temperature between 23.00 and 07.00 was 32.7°C for the living rooms and 31.3°C for the bedrooms. The living rooms also were the hottest space in the building with a mean temperature of 32.9°C and a maximum temperature of 34.8°C.

The results indicate the living room is the hottest monitored space in the building and occupants in Dutse Alhaji experienced a higher temperature compared to the occupants in

Lugbe. The indoor relative humidity was 21% - 76% for Lugbe and 15% - 66% in Dutse Alhaji, which is outside the comfort limit of 40% - 60% for the associated temperatures.

## Conclusions

The results from the post occupancy, environmental monitoring and comfort survey from different residential low-income buildings in two locations in Abuja, Nigeria were presented in this paper.

Across the different locations examined during the post occupancy evaluations, 80% reported being warm and hot on the thermal sensation scale with most reporting being 'not satisfied' with their thermal indoor environment. At least 50% were uncomfortable with the thermal conditions. This further suggests that occupants perceived higher indoor temperatures during the dry season.

The thermal comfort survey showed occupants' adaptability to high temperatures with a neutral and preferred temperature range of 28.2°C – 29.6°C and 25.4°C – 28.3°C respectively with most of the occupants in the naturally ventilated building experiencing higher temperatures compared to those in air conditioned buildings. The linear regression analysis to calculate neutral and preferred temperatures confirm the higher adaptation potential at Lugbe compared to the lower temperatures recorded in Dutse Alhaji. However, the difference in temperature between the air conditioned and naturally ventilated building was only about 2°C. Upon further investigation, it was clear that most of the occupants of air conditioned buildings did not use their air conditioners for cooling frequently owing to power cuts being very common in this area during the survey. Most of the occupants didn't find their thermal conditions acceptable and more than 70% of the spaces monitored in all case studies recorded temperatures above the comfort range.

Based upon the results from these four case studies and the wider survey of 90 other dwellings, the results suggest that most residents in the study areas of Abuja are not satisfied with their thermal environment and there is discomfort among occupants in residential building. Occupants prefer to be much cooler during the dry season, therefore there is a high dependence on air conditioning to improve their indoor thermal condition.

This prevalence of thermal discomfort highlights the need to explore the possibilities of reducing internal temperatures, particularly by passive means (fabric, shading, etc.) given the need to avoid or reduce the need for air conditioning. This paper has reported on four case study dwellings, but six further dwellings have since been monitored in detail and will be reported in the future.

## References

- Abubakar, I.R. (2014). Abuja, city profile, *Cities*, 41 (2014), pp 81–91
- Adaji, M., Watkins, R., and Adler, G., (2015). An investigation into thermal comfort in residential buildings in the hot-humid climate of sub-Saharan Africa: A field report in Abuja-Nigeria. In: *the proceedings of the 31st International conference on Passive and Low Energy Architecture (PLEA)*, Bologna, Italy, 9-11 September. Bologna: PLEA.
- Adekunle, T. and Nikolopoulou, M. (2016). Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Building and environment*. 103 (2016), pp. 21–35.
- Adunola, A.O., (2012). Urban residential comfort in relation to indoor and outdoor air temperatures in Ibadan, Nigeria. In: the 7th proceedings of Windsor conference, Cumberland Lodge, Windsor, UK, 12-15 April. London: NCEUB.
- Adunola, A.O., and Ajibola, K., (2012). Thermal comfort considerations and space use within residential buildings in Ibadan, Nigeria. In: *the 7th proceedings of Windsor conference*, Cumberland Lodge, Windsor, UK, 12-15 April. London: NCEUB.

British Standards Institute (BSI). (2008). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment lighting and acoustics, British Standards BSEN15251. London: BSI.

Djongyang, N. and Tchinda, R. (2010). An investigation into thermal comfort and residential thermal environment in an intertropical sub-Saharan Africa region: Field study report during the Harmattan season in Cameroon, *Energy Conversion and Management*, 51 (17), pp 1391-1397.

Nicol, J.F. and Roaf, S. (2005). Post-occupancy evaluation and field studies of thermal comfort. *Research and information*, 33(4), pp 338-346.

Olayiwola, A.L.M., Adeleye, O. and Ogunshakin, C.L. (2005). Public Housing Delivery in Nigeria: Problems and Challenges, XXXIII IAHS, September 27-30 2005, Pretoria South Africa.

Oyedepo, S.O. (2014). Towards achieving energy for sustainable development in Nigeria. *Renewable and sustainable energy reviews*, 34, pp 225-272.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Impact of the Microclimatic Conditions on Pedestrians' Thermal Comfort in Dubai

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**Abstract:** This paper investigated the influence of microclimatic conditions on pedestrians' thermal comfort in Dubai at different times of the year, aiming to extend the period when people can walk outdoors. Field investigation were conducted in two urban communities, Jumeirah Lakes Towers and The Greens, where pedestrians walk regularly to facilities. Three hundred random pedestrians were interviewed along daily utilitarian trips to and from the mosque, metro station, school and office buildings, at different times of day. The adaptive comfort measures, pedestrians' perception of the thermal environment and the walking distances they undertook were investigated. The thermal comfort and thermal sensation votes were recorded according to the ASHRAE scale and compared to the modified Physiological Equivalent Temperature mPET using RAYMAN. Findings revealed a steady discrepancy between the actual thermal sensation votes ATSV and mPET, the former underestimating pedestrian's thermal sensation. However, the index can be used to predict comfort under the local climate taking account of such difference. Findings revealed that the time of exposure that pedestrians endure in a space is more influential than its thermal conditions. The research provided an understanding of the thermal comfort conditions in Dubai, which ought to inform urban planners to encourage walkability.

**Keywords:** Dubai, Microclimate, mPET, Pedestrians, Thermal comfort

### Introduction

Pedestrians revitalise cities. Attractiveness and pleasantness significantly characterise the towns and districts where people walk and are rated as favourable environments. It is known that the microclimatic conditions of the outdoor environment, formed by the urban fabric, significantly undermine inhabitants' use of urban spaces (Zhang and Zhao, 2008). Over the past few years, the government of Dubai has launched several initiatives to promote walkability. These involve encouraging developers to create favourable environments with appealing outdoor spaces for people to enjoy walking on a regular basis and use their cars less. However, the challenging natural climatic conditions are exacerbated by the unfriendliness of the built environment and its anthropogenic heat sources. In many urban communities, walkability is seriously impaired by these factors and the lack of solar protection is an obstacle to comfortable walking for almost half the year. Many studies have shown, however, that people can tolerate unpleasant climatic conditions simply because they have come outdoors and decided to walk (Al-Sabbagh, 2011, Al-Sabbagh et al., 2016, Nikolopoulou et al., 2001). It is believed that understanding the impact of the various shade and wind conditions on people's perceptions should give urban designers the chance to manage the physical attributes of the spaces they create sensibly such that people would tolerate longer walks during warmer conditions.

However, the lack of studies of outdoor comfort and calibrated universal thermal comfort indices for local climates seem responsible for the challenge offered to urban designers and planners who seek to predict pedestrian's comfort measures and needs. This study is part of a research project to improve walkability in Dubai; it reports on the findings from field studies undertaken to assess pedestrians' thermal comfort and thermal sensations in a range of microclimatic conditions and seasons as they take utilitarian daily walks to such facilities as their work, school, the metro, the mosque, etc. The aim was to identify the walking distances and frequencies that pedestrians will tolerate in a range of microclimatic conditions and set the comfort limits as basis for future research.

### The Climate

The climatic conditions of Dubai ( $25^{\circ}\text{N}$   $55^{\circ}\text{E}$ ) is divided into three distinct periods (Al-Sabbagh and Yannas, 2015)(Figure 1): a four-month period of mild weather, December to March inclusive; two warm months, November and April; and a hot period, May to October inclusive (Yannas, 2008). This is when pedestrians enjoy walking even without protection from the sun. During the warm period, pedestrians start to experience discomfort due to higher air temperatures and humidity levels. In the hot period, the high temperatures combined with high humidity dramatically increase the sensation of discomfort, reducing the *tolerable* walking distances dramatically (Al-Sabbagh et al., 2016). A cooler breeze, often referred to as the 'Shamal', blows from the northwest, at an average speed of 3.8 m/s in the winter. When it comes from the desert (as a southerly or south-easterly breeze) it grows warmer and at speeds between 3.75 m/s and 7 m/s (Al-Sallal and Al-Rais, 2012).

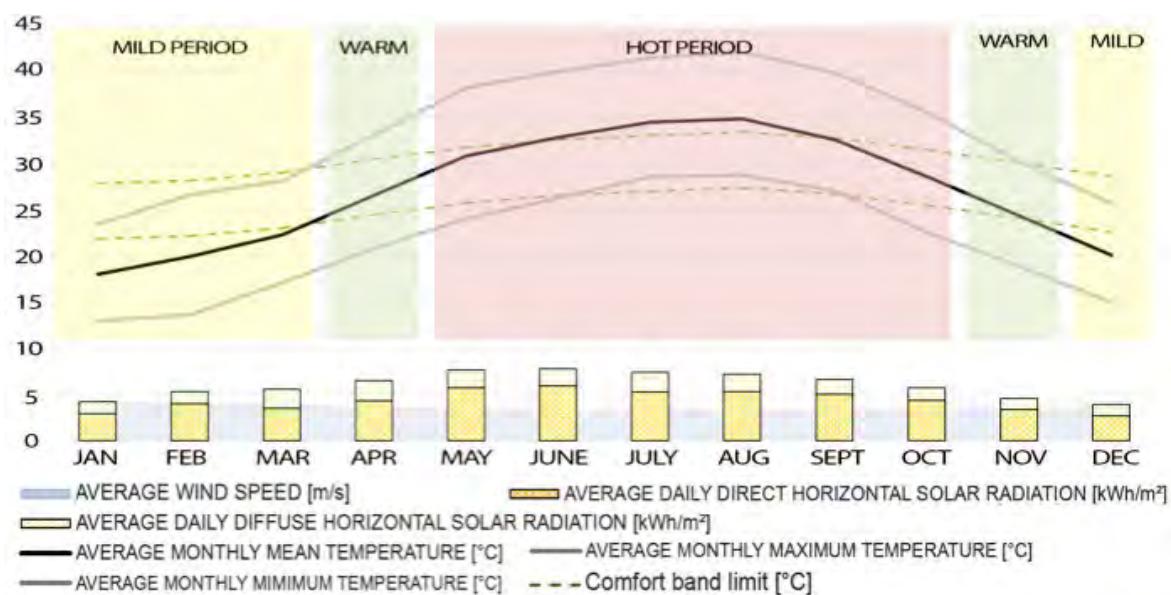


Figure 1. Average temperatures, wind speed and solar radiation for Dubai, showing the three climatic periods.

### Pedestrians Thermal comfort

Countless attempts have been made to define thermal comfort, but a general definition that has been accepted globally is that of ASHRAE: the state of mind that expresses satisfaction with the thermal environment (ASHRAE, 1997). Höppe (2002) considers this definition more descriptive of a psychological approach due to the subjectivity and wide variety of comfort levels. Analysis has found that psychological and behavioural adaptation has great influence

on people's satisfaction with the thermal environment. People's satisfaction with their surroundings differs from one place to another, depending on several subjective parameters (Nikolopoulou and Lykoudis, 2006). Nikolopoulou et al. (2001) summarize these as available choice, environmental stimulation, thermal history, memory and expectation. Nicol et al. (2012) argued that 'expectation' allows the thermal conditions anticipated to exert a major influence upon subjective assessment and satisfaction. In Dubai, a city with extremely hot summers, found that when the air temperature is 40°C people report that they coped with being outdoors (Balakrishnan, 2012)). Another psychological parameter of thermal comfort is 'choice'. This can be defined as a person's ability to choose to adapt to the surrounding environment and is sometimes known as 'perceived control' (Nikolopoulou and Lykoudis, 2006). Studies argue that this parameter allows people to tolerate higher variations of temperature than they can indoors, so long as they have chosen to go out or in. Moreover, 'thermal history' should be considered; this identifies the climatic conditions that an individual has adapted to for the past few years. For example, Taiwanese people prefer warmer conditions to those chosen by European nationals, due to the climatic conditions that each group has adapted to (Lin et al., 2010). Lin et al. (2009) finds that the thermal comfort of respondents in Taiwan varies between 21.30° and 28.50°C PET (Physiological Equivalent Temperature) significantly higher than that reported in Central Europe (18°-23°C). Taiwanese people most preferred 24.5°C Physiological Equivalent Temperature (PET) during the hot season and 23°C during the cold season. Therefore, the 'adaptive model' approach (Brager and de Dear, 2001) is suitable to investigate pedestrians thermal comfort because it is centred on the behavioural and subjective assessments of individuals in authentic settings and reflects more than the physical relationship between people and their environment. Nonetheless, consideration of the techniques and the number of subjects involved is critical to avoiding widely diverse results (Djongyang et al., 2010).

Thermal comfort is influenced by the state of physical activity, which is not the same for people sitting or resting and those walking: the latter experience higher metabolic rates, which require lighter clothing or higher wind speed to compensate for the discomfort felt. This is due to the mechanism of the human body as it seeks a state of equilibrium with the surrounding environment. Therefore, the variables of the outdoor thermal comfort cannot be used alone for accurate predictions about pedestrians in dynamic conditions, whether about their physical changes or the changes in their environment (Mayer, 1993). The physiological process is related either to the mean skin temperature in cold conditions or to the wetness of the skin caused by sweat secretion in warm conditions (Djongyang et al., 2010). This is greatly influenced by the balance between the surrounding humidity and the currents of air. As the wind flow increases, the evaporative losses from the skin surface increase, allowing the body to cool down. The presence of high humidity levels and lack of wind which trouble pedestrians in Dubai reduces the evaporative heat loss. Pedestrians feel this even more acutely, since walking increases their activity level and in turn the heat produced by the body (raising the metabolic rate). The higher the metabolic rate, the higher the associated thermal stress, because the heat that must be dissipated to achieve thermal comfort becomes greater. Studies also show that the metabolic rates rise by 11% for all activities performed in temperatures as they rise from 21.2°C to 37.8°C, but providing shade even without any reduction in air temperatures reduces the metabolic rate by 2%-5.2% below that produced by the same activity when exposed to the sun (Givoni, 1976).

## Fieldwork

Field observations were conducted between September 2015 and May 2016 inclusive avoiding June, July and August due to the low presence of pedestrians during these months. The interviews involved questioning random pedestrians in two urban communities, Jumeirah Lakes Towers and The Greens, Figure 2, where pedestrians enjoy walking on a regular basis to get to their desired destinations. In total, three hundred interviews were conducted along four utilitarian routes – daily journeys to work, school, the mosque and the metro – at different times of day (morning from 8:00-9:00, midday from 12:30-1:30 and afternoon from 16:00-17:00) when the patterns of pedestrians are evident.



Figure 2. Images of the two urban communities, *The Greens* on the left and *Jumeirah Lakes Towers* on the right, showing the different arrangement for providing shade in the pedestrian spaces.

Information about the subjects, such as their age, gender, clothing, duration of residence in Dubai and origin were gathered. Micrometeorological sensors were selected in accordance with the specifications outlined in ASHRAE's Handbook of Fundamentals (ASHRAE, 1997). The OHM Delta Thermal Microclimate HD32.2 logged the environmental parameters simultaneously known to influence thermal comfort every minute: temperature (Ta), relative humidity (RH) and wind speed (V). The shading conditions of the space and the antecedent space were also noted for help in analysing the influence of the thermal transitions on comfort. This involved people who walked out of the air-conditioned metro station. Subjective votes of thermal comfort (TCV) and thermal sensation (TSV) were noted on the ASHRAE scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot) for the TSV and (1 very comfortable, 2 comfortable, 3 just comfortable, 4 just uncomfortable, 5 uncomfortable, 6 very uncomfortable) for the TCV. Questions such as 'What bothers you most at this moment? Sun, heat, dust, etc.?' and 'How do you find the provision of shade along your journey?' were asked, in order to capture people's perception of their thermal environment. Questions were asked to analyse the distances that people walked and the frequency of their walks throughout the year. People were also asked if they owned a car and the length of time that they had lived in the city, to show how long they had had to adapt in.

## Findings on thermal sensation and thermal comfort

The thermal conditions of the air temperature, wind speed, relative humidity and radiant temperature were used to extract the modified Physiological Equivalent Temperature (mPET) using RAYMAN (Gulyás et al., 2006) and correlated to the actual votes. The clothing was set to 0.9 clo as the average value recognized by most pedestrians. In 2008, Lin and Matzarakis verified the usage of the Physiological Equivalent Temperature (the older version of the index) on the ASHRAE scale through a wide number of field surveys, providing a thermal sensation TS scale for people who lived in Taiwan as a representative of a subtropical climate. This scale was used to compare the votes for the present investigation. Pedestrians replied that

between 18° and 22° C they felt slightly cool, at 29°-30° C they felt slightly warm and between 31° and 37° C they felt warm, Figure 2. Thermal neutrality was achieved between 23° and 28° C, which extends slightly above the range found in previous studies (Lin and Matzarakis, 2008). The findings reveal a steady rise in the actual votes compared to those predicted by RAYMAN. This is found to be reasonable in view of the high metabolic rates of the pedestrians interviewed. Such aspect highlights the need for developing dynamic indices to predict pedestrians thermal comfort.

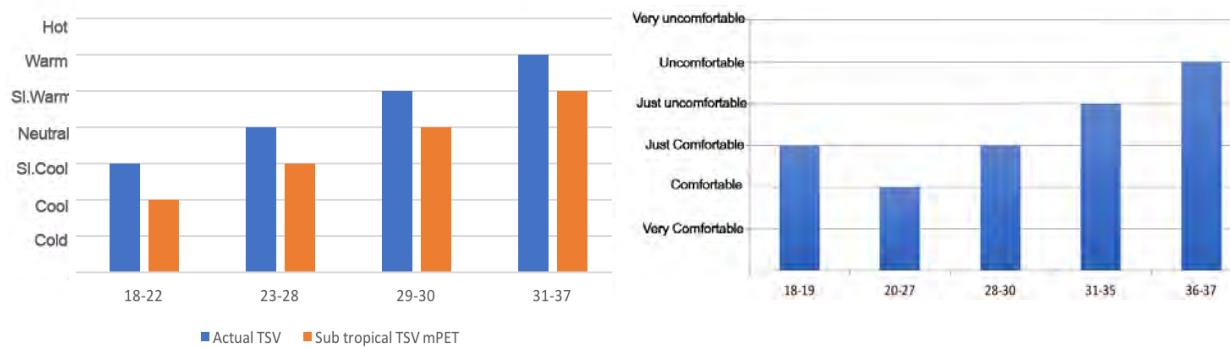


Figure 2. Two diagrams showing the average Actual Thermal Comfort Votes (right) and the average Actual Thermal Sensation votes compared to the mPET votes by RAYMAN (left).

Pedestrians' thermal comfort votes (TCV) were also classified according to the air temperatures noting that slight variations in wind speeds were recorded of average 1.2m/s. Pedestrians voted that between 18° and 19° C they felt just comfortable from the sensation of coolness; between 28° and 33° C they felt just comfortable, but just uncomfortable between 34° and 35°C and uncomfortable between 36° and 37°C, Figure 2. The comfort range can be identified in line with the votes of 'just comfortable', 'comfortable' and 'very comfortable' that were recorded between 18° and 30°C. At this range of comfort, pedestrians' TS ranged between slightly cool, neutral and slightly warm, which indicates that the interviewees were comfortable when they felt slightly cool or slightly warm. The replies of 'very comfortable', 'comfortable' and 'just comfortable' can be considered to lie within an accepted range of comfort named the *tolerable thermal comfort* range, which is between 18° and 30°C. A wider range of comfort, can involve the just uncomfortable votes being between 18° and 35°C. It is important to note that the wind variations were very small, on average 1.2m/s.

### Walking distances and frequencies

The surveys revealed that pedestrians walked for a great deal of the year in both the urban communities surveyed. 61 % of the pedestrians mentioned that they took the same route all year round, while 36% mentioned that they avoided walking in summer. Pedestrians who do not walk regularly account for only 3% and those who rarely walk only 1%. It should be borne in mind that the sample surveyed only people who had chosen to walk and were outdoors at the time. Also, some of the pedestrians depended on the metro in their daily transport. However, it has been noted that walkability did not depend upon owning a car, as some people argue; in the present study, only 54% of the pedestrians interviewed had private cars. They mentioned that they walked only when the weather was pleasant and 68% of them chose not to walk in the summer (defined as May to November). On the route between the

metro station and the office buildings, the flow of pedestrians was strongest during all year round. A few others also commented that the metro facility encouraged them to walk and depend less on their cars. The flow on Fridays at prayer time continued all year long, only slightly lessening during the hot period, even despite the lack of shade at various points on the route. Such findings highlight the influence of the psychological factors such as expectation, perceived control and thermal background on their votes. This could help planners understand the walking frequency to and from different facilitates when designing urban communities that promote walkability.

The findings revealed that in mild conditions people chose shorter routes in preference to cooler ones, which was not the same at warmer situations. In JLT, along the journey linking the metro station and office building, it was evident that most of the pedestrians used a short cut through the covered parking garage. This was a naturally ventilated semi-outdoor space. However, the space recorded higher air temperatures ( $3^{\circ}\text{--}7^{\circ}\text{C}$ ) and relative humidity levels during the warm and hot periods due to the heat anticipation from the cars accompanied by the lack of ventilation. When they were asked, they said that this route was shorter and shaded. This revealed that people's perception to thermal environment is more influential upon their choice of routes than the thermal conditions of the space. It also revealed that pedestrian's perception of shaded spaces as cooler ones is higher when the weather conditions gets warmer.

The distances that people walked depended mainly upon the distance between the facilities. As the climatic conditions worsened the frequency of pedestrians along the route went down but not the distances covered. Thus, in mild conditions the highest frequency of pedestrians was seen in the mornings, midday periods and afternoons along the routes investigated. During the warm period, the frequency during the morning and late afternoon slightly declined yet substantial numbers of pedestrians could still be seen. However, fewer of them were seen walking in the middle of the day. In the hot period, the numbers of pedestrians reduced dramatically but a few could still be seen. These pedestrians mostly owned no car. So, it can be inferred that during the hot period people who have any alternative such as a car choose not to walk. The notion of choice was very important. People who had cars perceived the conditions during the warm period as 'fine' while people who were forced to walk were the most troubled by the weather.

The pedestrians walking distances were measured by the time of their exposure to outdoor conditions rather than the distances cut. It was found that as the weather got warmer, the longer routes linking facilities were less occupied than they were during the mild period. 29 % of pedestrians walked for between 6 and 8 minutes, while 28 % walked for 9-11 minutes. Only 6% of pedestrians walked for between 1 and 2 minutes, 9 % from 12-14 minutes and 2 % walked for more than 15 minutes. Most pedestrians walked between 3 and 11 minutes, covering approximately 100-330m long at an average walking speed of 3.3 m/s. This was correlated to the fieldwork findings conducted earlier (Al-Sabbagh et al., 2016).

### Influence of thermal transitions

Moving from indoors to an outdoor shaded/non-shaded space influenced pedestrians in different ways. When people were interviewed immediately after they had moved from the mosque and the metro station (air-conditioned) to an outdoor space, were they have spent more than 10 minutes indoors, their thermal votes differed within the same time of the day and climatic period. The metro station exit was followed by a shaded space, while the mosques exits in both districts had no adjacent shade. During the mild period the TSVs

changed one step to being warmer in both shaded or non-shaded spaces. However, during the warm and hot conditions, their thermal votes changed for the worse when the building exit was followed by a non-shaded space compared to that when the building was followed by shade. This highlighted the importance of transitional spaces next to building exits to reduce the temperature difference between the indoor and outdoor. The effectiveness of such design increases as the weather conditions gets warmer, thus the temperature difference increases.

It was proved that the length of exposure that pedestrians endure in a space was more influential than the thermal conditions of the space. When pedestrians passed through a non-shaded space for a very short time (less than 2 minutes) their TCV did not change however, their TSV in some situations did. This corresponds with the findings from (Al-Sabbagh et al., 2016). Pedestrians are able to tolerate short non-shaded spaces as long as they are following by a shaded space that would improve their thermal sensation.

The measurements revealed that in general, shaded spaces were not necessarily cooler at different times of the day, given the high radiations from the various surfaces and the lack of ventilation. Spaces that were covered by trees revealed higher air temperatures during mornings at different times of the year. However, most people preferred the shaded spaces and perceived them to be cooler. During the warm and hot periods, almost half of the interviewees voted that the sun heat were the most bothering parameters while the others saw that the humidity was the main reason for discomfort. This was assured by the lack of wind, which reduced the chance for evaporative cooling of the skin. Especially that most pedestrians in Dubai wear more clothing than their counterparts in many hot cities. Many of the pedestrians, moreover, wore a suit, since they were on their way to or from work. Others were going to the mosque, which necessitates wearing long underwear and half sleeves. This highlights the need to provide cooler outdoor conditions for people under this climate. When people were asked if they took any measures, only 17% mentioned that they sometimes used an umbrella for shade' 4% used sunglasses, 6% used hats and only 4% mentioned that they would consider taking a cold drink/water. 3% said that they would use a hand-held fan if it was available. The Most people (66%) replied that they took no measures at all asserting that it was impractical to carry anything.

## Conclusions

It can be concluded that, during the mild season (December- January) pedestrians enjoy walking outdoors even at midday despite the lack of shade. When the climatic conditions drop below the comfort range, i.e. early morning in January or February, pedestrians adjust their clothing to feel 'comfortable', where pedestrians voted that they felt comfortable when 'slightly cool'. This confirms with Zhang's finding (2003) that people enjoy cool sensations. The other period of the year discomfort is endured depending upon the provisions provided. Pedestrian's along utilitarian trips have high tolerance to heat and proved to walk during long periods of the year avoiding non-shaded routes. Shaded spaces are perceived cooler and improved the TCV significantly even when they did not improve the microclimatic conditions. The influence of the psychological parameter was dominant in multiple situations and proved to have great potentials to improving thermal comfort. In general, at mild microclimatic conditions, changes within the thermal environment were not recognized by most pedestrians. The findings also highlight the need for providing transitional spaces next to building exits to reduce the temperature difference between the indoor and outdoor spaces particularly during the warm and hot conditions. Shorter distances between facilities would

promote walkability at different times of the year without the need for continuous shade. Further studies and field investigations in this region are greatly needed to improve the way open spaces are designed. Urban planers are obliged to refer to calibrated thermal indices to predict pedestrian's satisfactory levels and encourage walkability.

## References

- Al-Sabbagh, N. S. (2011) 'The impact of bioclimatic design on ambient air temperature in Dubai small outdoor urban spaces', British University in Dubai.
- Al-Sabbagh, N. S. and Yannas, S. (2015) 'Urban design and thermal comfort: Cooling for pedestrians in Dubai', *Proceedings of Ecocity World Summit*.
- Al-Sabbagh, N. S., Yannas, S. and Cadima, P. (2016) 'Improving Pedestrian Thermal Sensation in Dubai', *Proceedings of the 36th International Conference on Passive Low Energy Architecture in Los Angeles, USA*, Los Angeles, USA:
- Al-Sallal, K. A. and Al-Rais, L. (2012) 'Outdoor airflow analysis and potential for passive cooling in the modern urban context of Dubai', *Renewable Energy*, vol. 38, no. 1, pp. 40–49 [Online]. DOI: 10.1016/j.renene.2011.06.046.
- ASHRAE (1997) *ASHRAE Handbook: Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers. 1997.
- Balakrishnan, P. (2012) 'Cool spots in hot climates: A means to achieve pedestrian comfort in Sharjah, U.A.E.', MArch, AA School of Architecture.
- Brager, G. S. and de Dear, R. (2001) 'Climate, Comfort & Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55', Center for the Built Environment, University of California, Berkeley.
- Djongyang, N., Tchinda, R. and Njomo, D. (2010) 'Thermal comfort: A review paper', *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2626–2640 [Online]. DOI: 10.1016/j.rser.2010.07.040.
- Givoni, B. (1976) *Man, climate and architecture*, 2nd ed. Architectural science series, London, Applied Science Publishers.
- Gulyás, Á., Unger, J. and Matzarakis, A. (2006) 'Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements', *Building and Environment*, vol. 41, no. 12, pp. 1713–1722 [Online]. DOI: 10.1016/j.buildenv.2005.07.001.
- Höppe, P. (2002) 'Different aspects of assessing indoor and outdoor thermal comfort', *Energy and Buildings*, vol. 34, no. 6, pp. 661–665 [Online]. DOI: 10.1016/S0378-7788(02)00017-8.
- Lin, T.-P. and Matzarakis, A. (2008) 'Tourism climate and thermal comfort in Sun Moon Lake, Taiwan', *International Journal of Biometeorology*, vol. 52, no. 4, pp. 281–290 [Online]. DOI: 10.1007/s00484-007-0122-7.
- Lin, T.-P., Matzarakis, A. and Hwang, R.-L. (2010) 'Tourism climate and thermal comfort in Sun Moon Lake, Taiwan', *Building and Environment*, vol. 45, pp. 213–221.
- Mayer, E. (1993) 'Objective criteria for thermal comfort', *Building and Environment*, vol. 28, no. 4, pp. 399–403 [Online]. DOI: 10.1016/0360-1323(93)90016-V.
- Nicol, F., Humphreys, M. A. and Roaf, S. (2012) *Adaptive thermal comfort: principles and practice*, London ; New York, Routledge.
- Nikolopoulou, M., Baker, N. and Steemers, K. (2001) 'Thermal comfort in outdoor urban spaces: understanding the human parameter', *Solar Energy*, vol. 70, no. 3, pp. 227–235 [Online]. DOI: 10.1016/S0038-092X(00)00093-1.
- Nikolopoulou, M. and Lykoudis, S. (2006) 'Thermal comfort in outdoor urban spaces: Analysis across different European countries', *Building and Environment*, vol. 41, no. 11, pp. 1455–1470 [Online]. DOI: 10.1016/j.buildenv.2005.05.031.
- Yannas, S. (2008) 'Challenging the Supremacy of Airconditioning', *2A Architecture & Art*, no. 7, pp. 20–43.
- Zhang, Y. and Zhao, R. (2008) 'Overall thermal sensation, acceptability and comfort', *Building and Environment*, vol. 43, no. 1, pp. 44–50 [Online]. DOI: 10.1016/j.buildenv.2006.11.036.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Model View Definition (MVD) for Thermal Comfort Simulation in Conventional BEPS tools

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**Abstract:** Recent changes in peoples' lifestyles have contributed to a perceived improvement in their quality of life. However, this advance has been accompanied by a reduction in outdoor activities and reflected in issues of human health and well-being. When designing and creating a working or living space, the provision of thermal comfort for a building's occupants remains a significant objective but can be difficult to accurately quantify throughout design. Current demand for higher energy efficiency and improved indoor thermal comfort within the buildings sector have led to the use of Building Energy Performance Simulation (BEPS) tools. These powerful analytical tools allow evaluation of the indoor environment and energy performance at different stages of a building's life-cycle. However, integrating BEPS with Building Information Modelling (BIM)-based building design tools is still limited due to a lack of standardised methods of information exchange between these domains. The paper presents a Model View Definition (MVD), or subset of BIM relevant to a particular business process, for thermal comfort evaluation using conventional BEPS tools. In doing so, this work allows a standardised exchange of data from BIM to BEPS tools, for instance EnergyPlus. The role of MVD is to extract the necessary data for this exchange process in order to achieve optimum and reliable results of thermal comfort, in adherence with the Industry Foundation Classes (IFC) standard.

**Keywords:** Building Information Modelling (BIM); Model View Definition (MVD); Industry Foundation Classes (IFC) Thermal Comfort; Predicted Mean Vote (PMV).

### Introduction

The Architecture, Engineering, Construction, and Owner Operator (AECOO) industry is rapidly moving towards sustainable building design and development. The Building Research Establishment (2013) stated that 61% of the construction work would involve sustainable buildings or green building globally, between 2015 and 2018.

Energy demand and thermal comfort conditions can be predicted through digital simulation during the design stage. The failure of many buildings to meet the expectations of their designers is described as the "performance gap" (NBT,2015). Poor information management contributes significantly to uncontrolled variations in building design, operation and consequently to an increase in the performance gap. However, the energy performance of a building is only one aspect used to assess and determine the overall performance level. There are many important factors related to indoor environments that need to be accounted for when improving overall building performance, such as thermal comfort.

Building Information Modelling (BIM) is a life-cycle collaborative technology that is gaining rapid adoption within the AECOO industry. BIM is a universal user interface for architectural design and building performance simulations (Volk et al., 2014). When coupled, BIM and sustainable building design can not only reduce energy consumption and environmental effects but also can decrease costs and create a comfortable and pleasant living environment (Charles, 2003). Future integration of BIM with simulation tools is very promising (Cao et al., 2015). From the early design stage, BIMs contain useful information for different project elements that can be reused to create Building Energy Performance Simulation (BEPS) and thermal comfort models.

Of the available BIM formats, Industry Foundation Classes (IFC) is the only open life-cycle data model for buildings that is an international standard (ISO, 2013). As the IFC data model is so large, only carefully defined subsets of the model are required to support specific business processes. These subsets are called Model View Definitions (MVD), with the primary objective being to ensure standardised import and export of specific requirements for IFC compliant software (Pinheiro et al., 2015).

MVD is considered a sub-schema of the IFC schema specification and its main purpose is to select and specify the appropriate information entities (BuildingSMART, 2016). Information Delivery Manual (IDM) assists the development of user defined information exchange specifications. Thus, the MVD will bind all specified requirements in an IFC sub-schema. For example, if a BIM software has already implemented a MVD, the output IFC file will contain just the necessary exchange requirements pertinent to that MVD. Presently there is an absence of a MVD to support thermal comfort analysis in commercial buildings.

This paper presents a method for the integration of BIM and BEPS tools to perform thermal comfort analysis. It aims to identify a subset of data and information that needs to be included in IFC BIM before exporting the thermal model to BEPS tools through the development of a MVD. The outputs of this on-going project will contribute to a MVD for thermal comfort of commercial office spaces using the IFC standard.

### **Thermal Comfort and Workspace Occupant Satisfaction**

The World Health Organization (WHO, 1999) describes thermal comfort as a situation when people are pleased with the thermal environment, and that “health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”. According to the ASHRAE Standard 55 (2013), thermal comfort is “that condition of mind which expresses satisfaction with the thermal environment”.

It's clear that in practice, creating a suitable indoor thermal environment in workspaces makes an important contribution to employee productivity. As temperatures increase across the world and people are working indoors for longer hours through the day, the need for a comfortable working conditions and the concept of thermal comfort have gradually grown (Cheng & Das, 2014). In offices, the use of air conditioning and heating aims to provide thermal comfort, but every worker still seeks his or her personal thermally optimal preference (Harish, 2015). For example, recent studies show that females feel on average 3 (three) degrees Celsius colder than men (Geggel, 2015). Moreover, a study by Hellwig suggested that new heating and cooling legislations should take into account the average age, gender and body size of workers (Hellwig et al., 2006). Therefore, thermal comfort is not just related to air temperature alone. All factors noted above and others should be considered in the evaluation process, additionally to physiological and psychological factors (Figure 1).

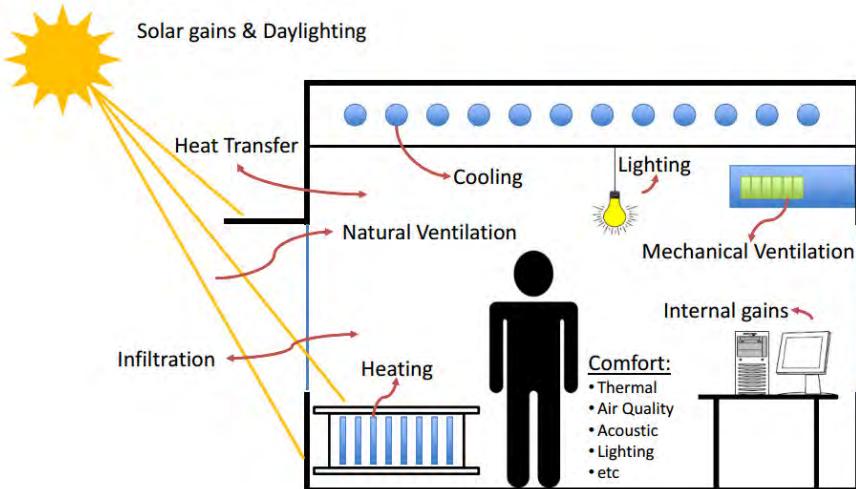


Figure 1: Factors that have effects on comfort level inside working spaces (Pinheiro et al., 2015)

## State of the art

When it comes to energy reduction and indoor condition prediction, energy modelling and simulation tools can be highly effective (Kim et al., 2015). However, most building energy analysis and thermal comfort evaluations have been conducted at a later point in the design phase. The ability to test alternative design solutions is typically not used in the early stages of design, due to the effort and cost of modelling a building geometry and its HVAC systems (Remmen et al. 2015). Today BIM provides building designers the ability to explore different energy saving alternatives and assess the indoor environment in the early design stage while avoiding the time-consuming process of re-entering all the building geometries and HVAC information to perform the required analysis (Stumpf & Kim., 2011).

Energy modelling using BIM has the potential to simplify the whole process by using the required information stored in an architectural or mechanical model. In doing that a significant time and efforts saving can be achieved during the BIM based data exchange (Rose & Bazjanac, 2015; Lili et al., 2017). However, there are a number of limitations reported in BIM based energy simulations, such as: difficulty in BIM data exchange, lack of HVAC system data, data inconsistencies, poor-quality data and uncertainty in building zoning (US GSA, 2012). These issues can lead to incorrect decisions by designers.

Most simulation software focus on building geometry to create a new simulation model or add modifications to a building geometry that has been imported from BIM (O'Donnell et al., 2011). HVAC information and control systems can be a complex issue for designers (Basarkar et al., 2012). This issue may be due to the large amount of input data for BIM models, including HVAC design data. However, the existence of this data within thermal model can be valuable to obtain reliable results for thermal simulation, but at the same time some of this data is unnecessary in the model when exporting a select zone of the building to perform thermal comfort analysis.

Thermal comfort simulation analysis requires detailed specification of the data and information that needs to be exchanged to support these processes. A BIM in IFC contains appropriate data and information for the analysis of the energy and indoor thermal comfort performance. This data must first be filtered and categorised in a standardised manner.

This paper uses the Information Delivery Manual (IDM), which is a standardised methodology that has been developed by BuildingSMART (BuildingSMART, 2016), to define the exchange requirements needed for thermal comfort and then creates the MVD which

will bind these requirements in an IFC sub-schema. This approach will allow data to be transferred through a higher level of automation. As well as decrease costs, reduce errors and improve decision making by collaborating digitally in a common data environment whilst streamlining workflows.

### **Requirement Analysis Models for Thermal Comfort**

In 1970 Fanger introduced two statistical methods to clarify comfort feelings namely, Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD). These models are still in use today, with slight modifications, and are defined in ASHRAE Standard 55 (ASHRAE 2013) and EN ISO 7730:2005 (ISO, 2005). Most conventional BEPS software can estimate thermal comfort level based on the PMV and the PPD (Welle et al., 2011). However, PMV can be described as a “static” model of human thermal comfort and works on input of environmental and personal factors. Therefore, these kinds of models fail to take personal preferences of individual users into account. An adaptive comfort model is included in recent BEPS tools release, particularly the current version of EnergyPlus (Cheng & Das, 2014).

Adaptive approaches take into account behavioural responses. The adaptive approach gives building occupants more freedom to become well adapted to their usual environments, including opening windows, turning on fans or adjusting clothing. Therefore, thermal comfort is dependent on multiple factors, such as indoor environmental conditions, user behaviour, properties of building materials, etc. Thus, thermal comfort simulation requires additional representative data about indoor environmental conditions and energy consumption.

EnergyPlus is one of the conventional simulation package for modelling cooling, heating, lighting, ventilation, and other energy aspects (Cheng & Das, 2014). In order to predict the indoor comfort level, EnergyPlus requires a minimum of two sorts of input data. The first input data is a text based file in the “.idf” format, containing data and information such as schedules, HVAC system, number of occupants, parameters for run control etc. The second input data is the weather file which has “.epw” format and contains information such as location, solar radiation and periodic weather data for a statistically representative year. For a successful thermal comfort simulation, EnergyPlus uses either a “heat balance model” or “heat and mass balance”. The key assumptions of the heat balance model are that each thermal zone can be modelled as “well-stirred”, meaning it has a uniform temperature throughout the zone. Heat transfer is also typically limited to one-dimensional across heat transfer surfaces (Cheng & Das, 2014).

Developing an IFC based holistic design system for integrating BIM models with design simulation tools is needed for the construction industry. However, most of the energy analysis applications including EnergyPlus are standalone and do not provide direct communication with BIM models (Balder & Katranuschkov, 2013). Therefore, improving information flow between BIM and BEPS tools, has the potential to reduce errors and therefore increase efficiency on both energy and comfort performance. This can be done via a set of exchange requirements in the form of data and information and improve ability for exchange between stakeholders of the AECOO industry.

### **Case study - BIM for Conventional Comfort Analysis**

Thermal comfort analysis requires detailed specification of the analysis processes combined with the data and information that needs to be exchanged to support these processes. The target of this paper is to describe this data and information in a standardised format by

using IDM method. As the IFC data model is so large, only carefully defined subsets of the model are required to support specific business processes, in this case thermal comfort analysis. These subsets are called Model View Definitions (MVD), where the primary objective of MVDs is to ensure standardised import and export functions of specific requirements for IFC compliant software.

A BIM-based CAD tool (ArchiCAD) was used to model the use case consisted of a single thermal zone (Figure 2). ArchiCAD allows the user to model both the architectural design and the Mechanical Electrical and Plumbing (MEP) systems in the same work environment. In this example, to enable control over the export to IFC we specified the necessary content for the exchange between BIM and BEPS. For the walls, roof and floor, each material layer was defined, including physical characteristics such as density ( $\text{kg}/\text{m}^3$ ), thermal conductivity ( $\text{W}/(\text{m.K})$ ), thickness (mm) and surface finishing. However, some elements related to material thermal properties are missing in IFC4 release (like solar refraction, coefficient of heat transfer and absorption coefficient). These properties can have impact on a building's energy and indoor comfort level. Thus, adding these missing properties is enhancement of analysis model (Table 1).

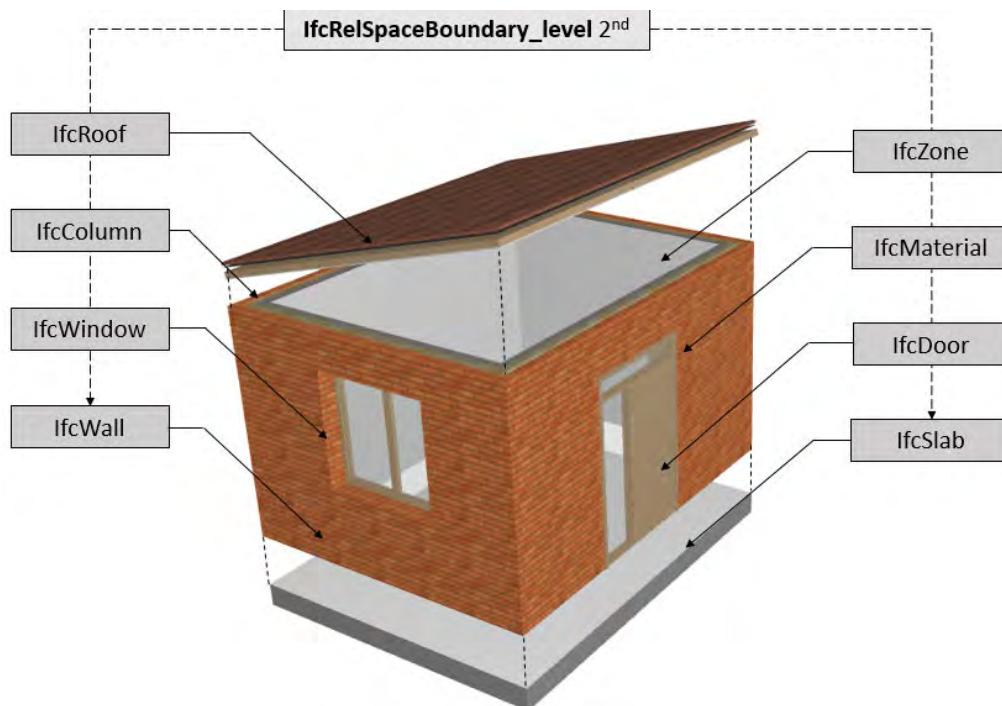


Figure 2: Case study, BIM representations of IFC data of room geometry.

The space boundary (IfcRelSpaceBoundary) defines the physical or virtualisation of a space as its relationship to the surrounding elements. Space Boundaries are needed to support different tasks such as energy estimation, lighting calculation, indoor evaluation and facility management (BuildingSMART, 2016). The use of Space Boundaries in this case study provide an accurate export of the architectural BIM with some level of pre-processing for thermal analysis software. In most cases there are two levels of space boundary implementations; Space surfaces boundaries, also referred as 1<sup>st</sup> level and thermal space boundaries, also referred as 2<sup>nd</sup> level. Each IFC exchange file can only contain boundaries of one single level, either 1<sup>st</sup> or 2<sup>nd</sup>. In this case study Space Boundary 2<sup>nd</sup> level is used. Elements in an IFC file that have to have space boundaries; [Walls – Slabs- Roofs- Columns - Windows and Doors- Openings (Virtual Elements) and Space Separators (Virtual Elements)].

After defining the exchange requirements necessary in IFC BIM model to perform analysis, an IFC file format will consist of the parameters required for specific analysis in this case, for thermal comfort evaluation.

### **Exchange Requirements for BIM to support Thermal Comfort Analysis**

IDM is used to document and describe the information that has to be exchanged between relevant stakeholders. It is important to firstly categorise these requirements in a standardised manner in order to subsequently develop a MVD for thermal comfort using the IFC standard.

With the aim of identify realistic information for evaluation of the comfort level within a zone such as that under discussion, a BIM-based environment was used to model the use case. This room was designed without introducing any mechanical equipment. The BIM model include 9 objects with over 194 properties relevant for thermal comfort analysis. These objects included Column, Door, Material, Roof, Slab, Space Boundary, Wall, Window and Zone. The results from this case study describe sets of essential properties needed for the integration of BIM with thermal comfort modelling before exporting the model into simulation tools, EnergyPlus. The following Table 1 summarises the basic requirements by entity types also presents overall definition and properties description for each entity.

The definition of property set is one of the main features of IFC. These sets provide valid substitutes to the definition of object/attribute/relationship sets for entities. In order to reduce the level of complexity, Figure 3 presents a small subset of zone data requirements for thermal comfort and provides underlying data for only one subset of exchange requirements of Table 1 (IfcZone). Each entity has many property sets that must be defined. In this case there is a set of properties under space thermal load that needs to be clearly defined before exporting an IFC based BIM data model to thermal comfort analysis tools. Each entity contains a property description field, for instance the maximum number of people assigned to this space over time, the Air exchange rate during a regular workday, the lighting level for this type of use and the equipment sensible assigned to this space, Air exchange rate and Dry-Bulb temperature etc. This information and others must be clearly defined per thermal load space instance in order to allow the building designers to make informed decisions and keep occupants within comfortable conditions.

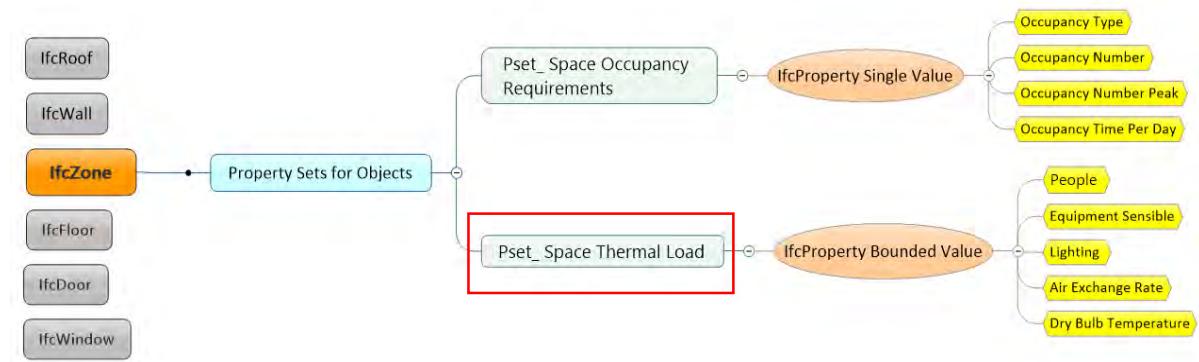


Figure 3 Graphical representation of one exchange requirements (IfcZone) for a partial Thermal Comfort MVD.

The example in (Figure 3) discusses only a subset of one IfcZone entity and the final MVD for thermal comfort analyses will contain all the exchange requirements and their relationships. The main purpose of a MVD, which is currently under development in this research project is to select and specify data and information are applied according to the exchange requirement of a particular process, in this case thermal comfort analysis.

Table 1: Exchange Requirements necessary from BIM to perform thermal analysis

Entity	Property Set	Property	Data Type	Unit
IfcDoor IfcWindow	Qto_DoorBaseQuantities	OverallHeight	IfcPositiveLengthMeasure	mm
	Qto_WindowBaseQuantities	OverallWidth	IfcPositiveLengthMeasure	mm
	Pset_DoorCommon Pset_WindowCommon	Reference	IfcIdentifier	--
		Infiltration	IfcVolumetricFlowRateMeasure	m³/s
		IsExternal	IfcBoolean	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m² K
		GazingAreaFraction	IfcPositiveRatioMeasure	m²
	Pset_DoorWindowGlazingType	Reflectivity	IfcPositiveRatioMeasure	--
		SolarHeatGainTransmittance	IfcPositiveRatioMeasure	m²K/W
IfcMaterial	Pset_MaterialEnergy	ViscosityTemperatureDerivative	IfcReal	Pa·s
		MoistureCapacityThermalGradient	IfcReal	--
		ThermalConductivityTemperatureDerivative	IfcReal	W/m.K
		SpecificHeatTemperatureDerivative	IfcReal	J/kg K
	Pset_MaterialThermal	SpecificHeatCapacity	IfcSpecificHeatCapacityMeasure	J/kg K
		ThermalConductivity	IfcThermalConductivityMeasure	W/m.K
	Ptc_MaterialThermal	SolarRefraction	IfcReal	--
		CoefficientOfHeatTransfer	IfcCoefficientOfHeatTransfer	W/(m²K)
		AbsorptionCoefficient	IfcAbsorptionCoefficient	--
IfcSlab IfcRoof	Pset_SlabCommon Pset_RoofCommon	Reference	IfcIdentifier	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m²K
		IsExternal	IfcBoolean	--
		PitchAngle	IfcPlaneAngleMeasure	radian
	Qto_SlabBaseQuantities Qto_RoofBaseQuantities	Width	IfcLengthMeasure	mm
		Length	IfcLengthMeasure	mm
		Depth	IfcLengthMeasure	mm
		GrossArea	IfcAreaMeasure	m²
		NetArea	IfcAreaMeasure	m²
		GrossVolume	IfcVolumeMeasure	m³
IfcWall IfcColumn	Pset_WallCommon Pset_ColumnCommon	NetVolume	IfcVolumeMeasure	m³
		Reference	IfcIdentifier	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m²K
		IsExternal	IfcBoolean	--
	Qto_WallBaseQuantities Qto_ColumnBaseQuantites	Length	IfcLengthMeasure	mm
		Width	IfcLengthMeasure	mm
		Height	IfcLengthMeasure	mm
		GrossSideArea	IfcAreaMeasure	m²
		NetSideArea	IfcAreaMeasure	m²
		GrossVolume	IfcVolumeMeasure	m³
IfcZone	Pset_SpaceOccupancyRequirements	NetVolume	IfcVolumeMeasure	m³
		OccupancyType	IfcLabel	--
		OccupancyNumber	IfcCountMeasure	--
		OccupancyNumberPeak	IfcCountMeasure	--
		OccupancyTimePerDay	IfcTimeMeasure	--
		AreaPerOccupant	IfcAreaMeasure	m²
	Pset_SpaceThermalLoad	MinimumHeadroom	IfcLengthMeasure	mm
		People	IfcPowerMeasure	W
		EquipmentSensible	IfcPowerMeasure	W
		Lighting	IfcPowerMeasure	W
		AirExchangeRate	IfcPowerMeasure	W
		DryBulbTemperature	IfcPowerMeasure	W
		RelativeHumidity	IfcPowerMeasure	W
		TotalSensibleLoad	IfcPowerMeasure	W
		InfiltrationSensible	IfcPowerMeasure	W

## Conclusion

This paper presents a standardised process of information exchange between BIM and BEPS tools. This process is based primarily on the IDM/MVD methodology for implementation and documents the data exchange requirements for thermal comfort analysis using IFC. A use case identified the existing and missing objects in the latest release of the IFC schema that are relevant for thermal comfort analysis.

IFC includes a wide scope of the AECOO industry and is commonly used as the neutral file format for BIM models. However, there are a number of limitations of exchange data between IFC BIM model and BEPS environment to perform thermal comfort analysis. This

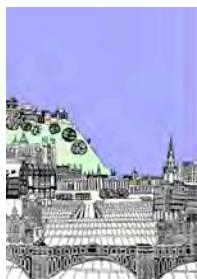
work reduces the difficulty of data exchange and improves the quality of data transferred between these two domains. The proposed MVD allows data to be transferred using higher level of automation and data consistencies, which can result in less manual work and reduce simulation analysis errors.

The key outcome from this work will have significant impact on the AECOO industry, in terms of time-saving, cost analysis and reduced hours of labour. This work can also improve decision making by collaborating digitally in a common data environment whilst streamlining workflows.

The next step in this research will include the development of a complete MVD to analyse thermal comfort levels in a commercial office based on the methodology employed in this paper. This step will also include testing and validation of the proposed MVD. After completion, the MVD will be submitted to BuildingSMART group for acceptance and publication as an official MVD for thermal comfort using the IFC standard.

## References

- ASHARE, 2013. ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy. *American Society of Heating, Refrigeration and Air conditioning Engineers*, ASHRAE Sta, p.58.
- Basarkar, M. & Donnell, J.O., 2012. Mapping Hvac Systems for Simulation in Energyplus. *SimBuild IBASA*, (July), pp.25–31.
- BuildingSMART, 2016. IFC Releases. *Interational home of openBIM*. Available at: <http://www.buildingsmart-tech.org/specifications/ifc-overview>
- Cao, J. et al., 2015. A Flexible Model Transformation To Link Bim With Different Modelica Libraries For Building Energy Performance Simulation. In *14th IBPSA Hyderabad*, India:, pp. 434–441.
- Cheng, J.C.P. & Das, M., 2014. A bim-based web service framework for green building energy simulation and code checking. *Journal of Information Technology in Construction*, 19(January), pp.150–168.
- Geggel, L., 2015. Cold Comfort: Why Office Air Conditioning Is Biased Against Women. *Human Nature*. Available at: <http://www.livescience.com/51729-office-air-conditioning-energy-costs.html>
- Harish, A., 2015. How to Improve Thermal Comfort in an Office Environment. *SimScal*. Available at: <https://www.simscale.com/blog/2016/07/improve-thermal-comfort-office/>
- Hellwig, R.T., Brasche, S. & Bischof, W., 2006. Thermal Comfort in Offices – Natural Ventilation vs . Air Conditioning. *Conference Comfort and Energy Use in Buildings. Getting them Right*.
- ISO, 2005. ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. pp.605–615.
- Kim, J.B. et al., 2015. Developing a physical BIM library for building thermal energy simulation. *Automation in Construction*, 50(C), pp.16–28. Available at: <http://dx.doi.org/10.1016/j.autcon.2014.10.011>.
- Lilis, G.N., Giannakis, G.I. & Rovas, D. V., 2017. Automatic generation of second-level space boundary topology from IFC geometry inputs. *Automation in Construction*, 76, pp.108–124.
- NBT, N.B.T., 2015. WHAT IS “THE PERFORMANCE GAP”? *Natural Building Technologies*. Available at: <https://www.natural-building.co.uk/news/what-performance-gap/>
- O'Donnell, J.O. et al., 2011. SIMModel : A Domain Data Model For Whole Building Energy Simulation. In *Proceedings of the 12th IBPSA Conference*. Sydney,Australia: 14-16 November., pp. 14–16.
- Peter Katranuschkov, R.B., 2013. *Introduction to the HESMOS project*, Dresden. Available at: [http://ises.eu-project.info/workshop-2013-10/01\\_Session\\_1\\_HESMOS-Introduction\\_to\\_the\\_HESMOS\\_project.pdf](http://ises.eu-project.info/workshop-2013-10/01_Session_1_HESMOS-Introduction_to_the_HESMOS_project.pdf).
- Pinheiro, S. et al., 2015. Development of a Model View Definition for Environmental and Energy Performance Assessment. In *2nd conferenceof the CITA BIM November 12th -13th 2015*. Dublin, Ireland
- Remmen, P. et al., 2015. An Open Framework For Integrated Bim-Based Building Performance Simulation Using Modelica. *Proceedings of Building Simulation 2015.*, Germany .
- Rose, C.M. & Bazjanac, V., 2015. An algorithm to generate space boundaries for building energy simulation. *Engineering with Computers*, 31(2), pp.271–280.
- US.GSA, Administration, 2012. *GSA BIM Guide Series 05*, Available at: [https://www.gsa.gov/portal.mediald/227111/fileName/GSA\\_BIM\\_Guide\\_Series](https://www.gsa.gov/portal.mediald/227111/fileName/GSA_BIM_Guide_Series).
- Stumpf, A. & Kim, H., 2011. *Early Design Energy Analysis Using BIMs (Building Information Models)*, Champaign,. Available at: <http://link.aip.org/link/?ASCECP/339/44/1>.
- Volk, R., Stengel, J. & Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38, pp.109–127.
- Welle, B., Haymaker, J. & Rogers, Z., 2011. ThermalOpt: A methodology for automated BIM-based multidisciplinary thermal simulation for use in optimization environments. *Building Simulation*, 4(4), pp.293–313.
- World Health Organization (WHO), 1999. *Health is a state of complete physical, mental and social well being and not merely the absence of disease or infir- mity*, Geneva.



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*Design to Thrive*

## Envelope Design and Thermal Comfort Performance in a High-Rise Office Building in Saudi Arabia

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**Abstract:** Thermal comfort is a key aspect when assessing a sustainable building's performance. In hot climates, such as Saudi Arabia, achieving comfort can require large amounts of cooling energy if the building has not been designed to take advantage of passive cooling techniques. In this study a thermal model of a real high-rise office building in Saudi Arabia was created and used to predict internal air temperatures, comfort levels and energy consumptions using *DesignBuilder*® software for summer days. Field measurements of comfort levels and internal temperatures were taken in the actual building to compare with the modelled data to check for acceptable agreement, and a small thermal comfort survey with office workers was also undertaken. The as-built office model was then parametrically altered for a range of passive strategies (including glazing area, insulation levels and thermal mass) to identify the most effective approaches to reducing cooling energy demand. The resultant optimized building was then tested under future climate scenarios for Saudi Arabia to check if the identified solutions were still effective. The study revealed that certain passive approaches could be applied successfully while maintaining an acceptable corporate image for the building – this was true for both current and future climates. The potential contribution of this study is the identification and testing of thermal comfort strategies to be used in the early design stages which will facilitate architectural design processes, practice and education.

**Keywords:** Built Environment, Thermal Comfort, High-Rise buildings, Architecture Technology, Sustainable Buildings

### Introduction

Global warming and sustainable development have become key issues for the built environment. Architects and engineers now need to consider any financial or environmental implications of their designs during the building's life (Holmes and Hacker, 2007). A key consideration in a sustainable strategy is the need to evaluate the role of fabric design efficiency and its impact on human thermal comfort. In countries with predominantly hot dry climates, such as Saudi Arabia, achieving thermal comfort can require substantial amounts of cooling energy. This problem can be exacerbated by the design of the building's external envelope. The appearance of many modern office buildings in Saudi Arabia resembles those seen in the USA or Europe, where the climates can be much less demanding in terms of thermal comfort. A first step in reducing the cooling energy demand of Saudi offices is to investigate the potential impacts that passive design measures applied to the building envelope, such as thermal insulation and thermal mass, can have in maintaining comfort whilst reducing cooling energy consumption.

This study used an actual office in Dhahran, Saudi Arabia to assess actual energy use and thermal comfort and then undertook a parametric analysis using a range of passive envelope measures. Summer conditions were chosen as they obviously represent the biggest test to the building envelope's thermal cooling performance. The dynamic simulation software *DesignBuilder*<sup>®</sup> was used to predict hourly values of operative temperature inside a zone of the office building. Predicted values from *DesignBuilder*<sup>®</sup> were compared to monitored data from the observed office.

## Background

Saudi Arabia's main sources of energy are oil and natural gas. The country burns more than one million barrels of oil per day to generate electricity (Alshehry and Belloumi, 2015). Electrical energy usage in Saudi Arabia has risen sharply in the last twenty-five years because of population growth, strong economic development and the lack of energy efficiency measures. Electricity consumption per capita in Saudi Arabia is approximately three times the global average (Naif, 2012). It has been estimated that around 73% of the electricity produced in Saudi Arabia is used in buildings, with 65% of that consumption being for air conditioning (Saudi Electricity Company, 2015).

There is now a growing interest and requirement to make Saudi buildings more sustainable. Decisions such as working on local building codes, enforcing insulation other sustainable treatments in construction have been considered to manage total building energy consumption. This includes any environmental friendly treatments during design concepts, construction process and building operation in order to conserve the environment (Mujeebu and Alshamrani, 2016). Mujeebu and Alshamrani (2016) highlighted that US\$26 billion has been invested in 76 green building projects across the country. This includes the King Abdullah financial district, which is one of mega green projects around the world. Furthermore, 90,000 eco-friendly mosques have been identified in the government's plans across the country to adapt green buildings as new choice of construction. Thus, Alyami and Rezgui (2012) suggested that the USA building standard LEED could provide the basis of a Saudi version in order to combine both national and local considerations.

Office buildings account for 14% of total building energy consumption in Saudi Arabia, and so are an important building type for energy efficiency design and retrofit (Al-Ghamdi et al, 2015; Alyousef and Abu-Ebid, 2012). In their review paper of 25 years of cooling research in office buildings, Prieto et al (2017) suggested that cooling research for offices in hot-arid climates was much less common than for offices in more temperate climates, but that this was changing. Recent projects have been undertaken in Middle East Gulf countries that have focused on the evaluation of passive cooling strategies; for example, the energy performance of shading systems (Freeman, 2014), the evaluation of glazing properties (Bahaj et al, 2008), the effectiveness of multi-facade systems (Radhi et al, 2013) and the efficiency of passive envelope measures (Friess and Rakhshan, 2017).

This study has concentrated on passive envelope measures, such as thermal insulation and glazing specification. An actual office block in Saudi Arabia was identified and monitored. Then, aspects of the office's envelope were parametrically altered and modelled to assess what impact the changes had on internal temperatures and thermal comfort conditions in the office.

## Methodology

This study used thermal comfort performance as the metric to assess the impact of applying different passive envelope approaches to an existing high-rise office tower in Dhahran, Saudi Arabia during severe climatic conditions in summer. Thermal comfort is defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) as “*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*” (ANSI-ASHRAE Standard 55, 2013). Ruppa et al (2015) reviewed the two basic ways of approaching thermal comfort in buildings – the Fanger model (1970) and the adaptive model (Nicol et al, 2012). This study has adopted the Fanger model (1970) as it is more relevant for air-conditioned spaces, such as those found in Saudi office buildings. Fanger’s model is quantified in terms of the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). PMV relates to a seven point thermal scale that ranges from Cold (-3), through Neutral (0) to Hot (+3). The recommended acceptable PMV range for thermal comfort in ANSI-ASHRAE Standard 55 is between -0.5 and +0.5 for an interior space. PPD predicts the percentage of occupants that will be dissatisfied with the thermal conditions. PPD is a function of PMV, and as PMV moves away from 0 (neutral), PPD increases. Because thermal comfort is subjective then it is never possible for everyone in a space to be comfortable all of the time. In ANSI-ASHRAE Standard 55 the recommended acceptable range for thermal comfort is for PPD to be less than 10% for an interior space. The dynamic thermal modelling software *Designbuilder®5.0* was used for this study as it is able to analyse energy consumption, comfort levels and other built environment parameters on an annual, monthly, daily or hourly basis depending on the study’s requirements.

For this paper, a typical summer day was selected for the analysis and environmental assessment. The office building used in the study was located in Dhahran, Saudi Arabia, and was 13 storeys high. Figure 1 shows the geometry of the simulated version of the building. The internal layout consisted of both open plan and cellular office spaces, and for the initial analysis an open plan office facing to the north – east, in the form shown in Figure 2, was selected.

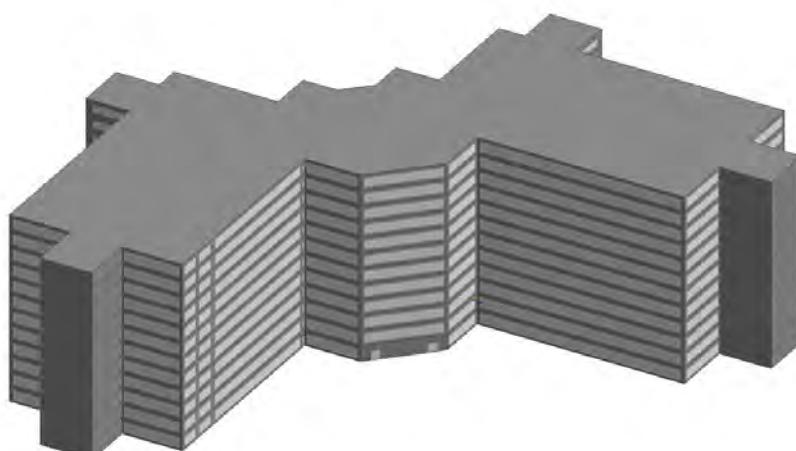


Figure 1.The geometry of the tested office building

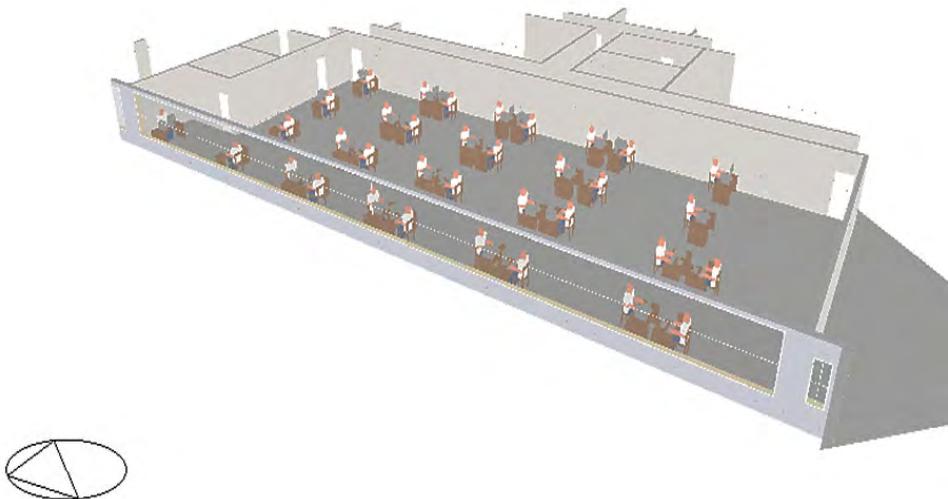


Figure 2.The selected zone of the study

The constructional and material details of the building were acquired from a site visit and Tinytag data loggers were positioned around the open plan office to measure air temperature and relative humidity levels over a two-week summer period. A virtual model of the office was created in *Designbuilder®5.0* and simulations of the predicted performance were undertaken. Data from the modelling were compared to the measured results from the dataloggers to check the *Designbuilder®5.0* model's reliability. Finally, *Designbuilder®5.0* was used to make parametric changes to the existing office to see if thermal comfort performance could be improved by passive measures. The passive measure considered in this study were insulation thickness and choice of glazing system.

## Results

### ***Reliability of Designbuilder®5.0 model***

Table 1 shows a comparison between the measured and modelled data for the open plan office for one of the summer days. For the hottest part of the day, when the office is most used, the agreement is good. This indicates that the settings chosen in the *Designbuilder®5.0* model (such as occupancy profile and set point values) are appropriate. Validation of the *Designbuilder®5.0* model gives confidence for the parametric analysis.

Table 1. Sample of the compared temperature data between simulation and field measurement readings in open plan office – typical summer day in Dhahran , Saudi Arabia.

Time	Measured air temperature [°C]	Modelled air temperature [°C]	Percentage difference (%)
13:00	24.5	23.6	3.6
14:00	23.8	23.5	1.3
15:00	23.3	23.4	-0.4
16:00	22.6	23.4	-3.5

### Parametric analysis for thermal insulation

Figure 3 shows the existing construction of the open plan office's envelope (A), consisting of an external aluminium cladding, a 75mm air gap, 200mm concrete hollow block and a gypsum plasterboard internal finish of 12mm. For the parametric analysis increasing thicknesses of thermal insulation were inserted in to the air gap until the air gap was totally replaced by the insulation for the treated envelope (B).

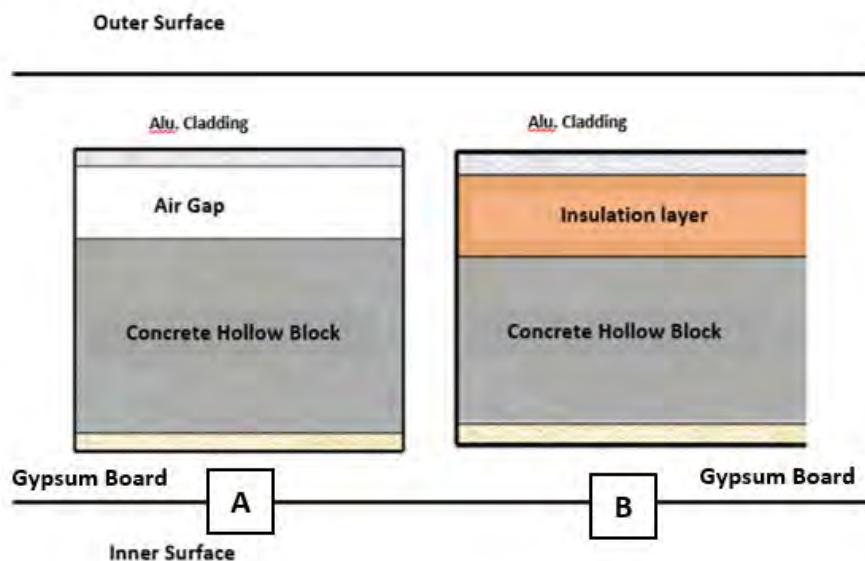


Figure 3. Cross section through the used walls in this paper while (A): existing office construction combination, base case and (B) is developed case with insulation.

Figure 4 shows the hourly internal air temperatures in the modelled office for the existing office and the insulated office over a 12 hour period. It can be seen that throughout the working day the base case façade would always create a warmer temperature in the office compared to the insulated office. There is a small but consistent difference in temperatures for the two envelope designs, and because these differences exist over many hours then this would be reflected as differences in the cooling energy required. Over an entire summer, the additional cooling energy consumed by the base case office would become noticeable.

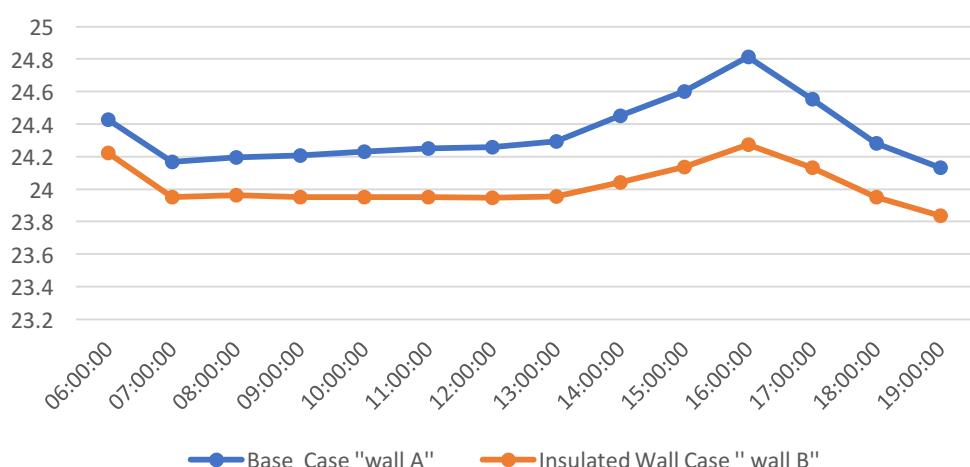


Figure 4. Modelled hourly average air temperatures for the existing office construction and the insulated office. .

Based on the predicted environmental conditions and assumed clothing and activity levels of the office workers, it was possible for *Designbuilder®5.0* to calculate the PMV and PPD values for the existing and insulated office set-ups. Figure 5 shows the results of the thermal comfort analysis. Adding the insulation to the office's envelope improved thermal comfort, with the PMV for the existing office moving from +0.6 (which is outside the ANSI-ASHRAE Standard 55 comfort range of -0.5 and +0.5) to a PMV of +0.2 when the insulation was in place.

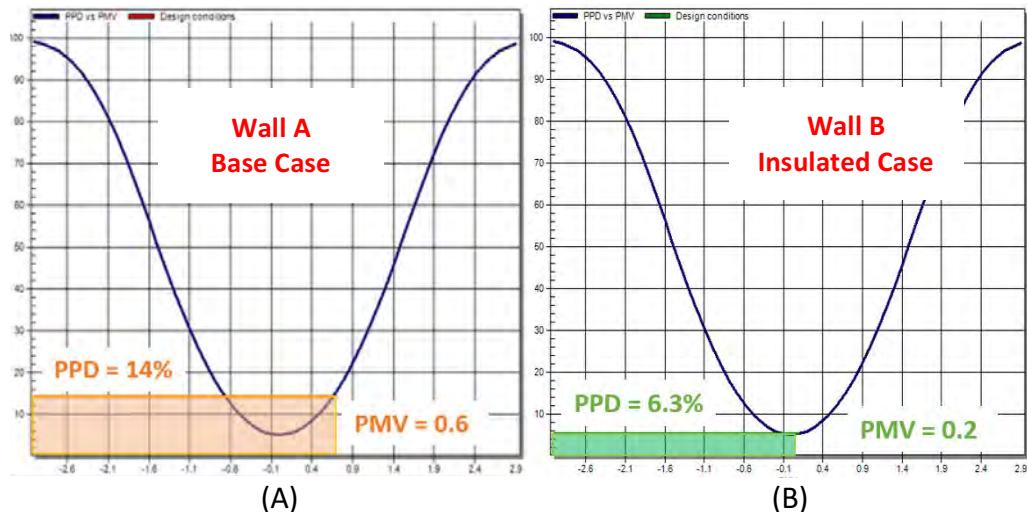


Figure 5. Thermal comfort graph for (A) existing office and (B) insulated office.

#### Parametric analysis for glazing choice

Fenestration is another key factor in envelope performance analysis for a hot arid climate, and so a second study examined the impact of replacing 6mm thick single glazing in the base case office with good quality double glazing consisting of two 6mm panes and a 13mm thick, argon-filled spacing (see Figure 6).

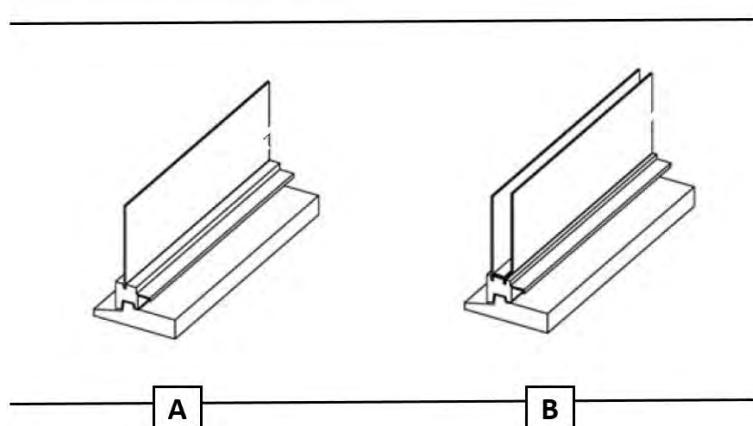


Figure 6. Isometric illustration of the used glazing in this paper when window (A) is single clear glazing, base case and (B) is developed case with double glazing and fill of air between pans.

Figure 7 shows the hourly internal air temperatures in the modelled office for the existing base case office and for the office with the higher specification glazing over a 12 hour period. It can be seen that base case glazing (A) would increase internal temperatures by 1-1.5% compared to the double glazed office (B). Over a long cooling season these small differences in temperature would be evident in terms of higher cooling energy costs for the base case office.

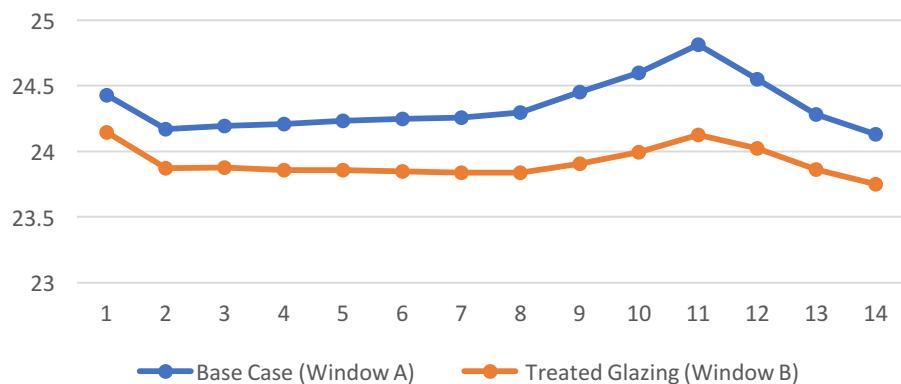


Figure 7. Modelled hourly average air temperatures for the existing office glazing and the office with the higher specification glazing.

Figure 8 shows the results of the thermal comfort analysis for the new glazing. Changing the glazing for the office's envelope improved thermal comfort, with the PMV for the existing office moving from 0.6 to a PMV of 0.1 when the treated glazing was in place.

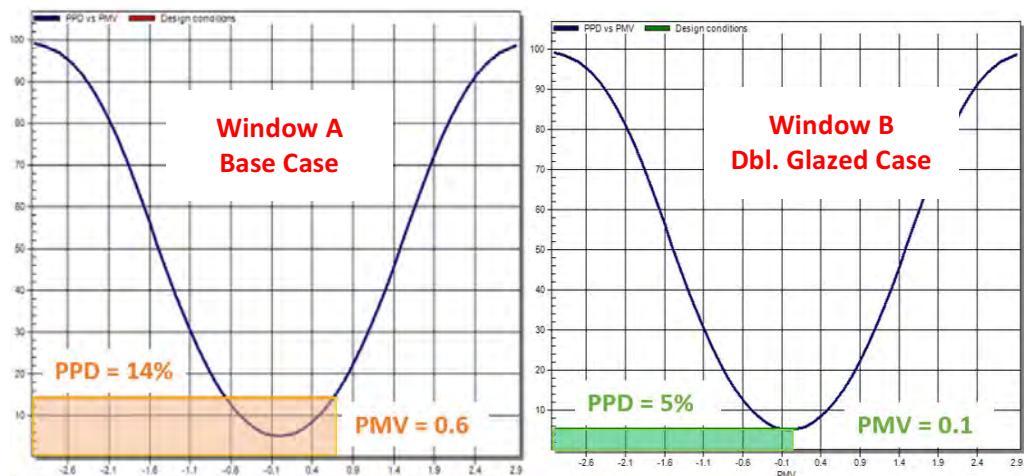


Figure 8. Thermal comfort graph for (A) existing office and (B) improved glazing office.

## Discussion and Conclusion

This paper describes initial findings from a larger study that is investigating a range of passive envelope interventions to reduce cooling loads and improve thermal comfort in high-rise office buildings in Saudi Arabia, both for current and future climatic conditions. These preliminary results highlight that even simple passive changes to envelope design can be effective, even in the very demanding hot arid conditions of a country such as Saudi Arabia.

## References

- Al-Ghamdi, S.A., Al-Gargossy, A. and Alshaibani, K.A. (2015). Energy conservation by retrofitting: an overview of office buildings in Saudi Arabia. International Conference on IT, Architecture and Mechanical Engineering (ICITAME'2015) May 22-23, Dubai (UAE).
- Alyami, S. H. & Rezgui, Y. (2012). Sustainable building assessment tool development approach. *Sustainable Cities and Society*, 5, 52-62.
- Alyousef, Y. & Abu-Ebid, M. (2012). *Energy efficiency initiatives for Saudi Arabia on supply and demand sides*, 279-308, INTECH Open Access Publisher.
- Alshehry, A. S. and Belloumi, M. (2015). Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia. *Renewable and Sustainable Energy Reviews*, 41, 237–247.
- ANSI/ASHRAE Standard 55 (2013)—Thermal Environmental Conditions for Human Occupancy, ASHRAE.
- Bahaj, A.S., James, P.A.B. & Jentsch, M.F., (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings*, 40, 720–31.
- CEN, E. (2007). 15251-2007, Criteria for the indoor environment including thermal, indoor air quality, light and noise. Brussels: European Committee for Standardization.
- Fanger, P.O., *Thermal Comfort: Analysis and Applications in Environmental Engineering*, Danish Technical Press, Copenhagen.
- Freeman, A.A.Y., (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*, 102, 14–30.
- Friess, W.A. & Rakhshan, K. (2017). A review of passive envelope measures for improved building energy efficiency in the UAE. *Renewable and Sustainable Energy Reviews*, 72, 485-496.
- Holmes, M.J. & Hacker, J.N. (2007). Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. *Energy and Buildings*, 39, 802–814.
- Mujeebu, M. A. & Alshamrani, O. S. (2016). Prospects of energy conservation and management in buildings - the Saudi Arabian scenario versus global trends. *Renewable and Sustainable Energy Reviews*, 58, 1647-1663.
- Naif, M. (2012). In: *Energy Efficiency Potential in the Building Sector*, The Saudi International Advanced Materials Technologies Conference 2012, KACST, Kingdom of Saudi Arabia.
- Nicol, F., Humphreys, M. & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Routledge, Abingdon.
- Prieto, A., Knaack, U., Klein, T. & Auer, T. (2017) 25 years of cooling research in office buildings: review for the integration of cooling strategies into the building façade. *Renewable and Sustainable Energy Reviews*, 71, 89-102.
- Radhi, H., Sharples, S. & Fikiry F. (2013) Will multi-facade systems reduce cooling energy in fully glazed buildings? A scoping study of UAE buildings. *Energy and Buildings*, 56, 179–88.
- Ruppa, R.F., Vásquez, N.G. & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, 105, 178–205.
- Saudil Electricity Company (2015). Annual Report, <https://www.se.com.sa/en-us/Pages/AnnualReports.aspx>



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Residential Balcony in the Mediterranean Climates

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**Abstract:** Residential balconies have gradually lost their traditional function as useful outdoor spaces on high-rise apartment buildings. At the same time the attraction of a private outdoor space continues to be very high in Mediterranean climates. This paper focuses on the microclimates of balconies and how these also impinge upon the environmental conditions of the adjacent rooms, as well as on the respective spaces on the floor below. The impact of different balcony typologies and the effectiveness of different shading devices were investigated through simulation studies and measurements undertaken in July 2016 in Thessaloniki, Greece, where balconies feature on every residential building. The findings are summarised in the form of operational recommendations for different balcony configurations as well as balcony design and solar protection options. These can be applied to new or existing residential buildings ensuring usability and functionality of the balcony area, as well as potential improvements to the energy balance of adjacent indoor spaces.

**Keywords:** shading devices, Mediterranean climate, transitional spaces, balcony

### Introduction

Balconies are an integral element on the facade of residential buildings in many countries with mild climates, such as the Mediterranean, providing an easy access to outdoors. Apart from its architectural, functional and social roles, the common balcony can influence the indoor environment of its parent building, as well as create a distinct microclimate of its own. Song and Choi (2012) found indoor spaces with attached balconies to maintain temperatures some 0.8K higher in winter achieving space heating and cooling savings of up to 39% and 22% respectively. Florides et al.(2002) reported that the presence of an overhang could yield up to 19 % in cooling energy savings in Cyprus, while studies by Chan and Chow (2010) demonstrated cooling savings can be achieved regardless of orientation with the highest savings for South-Westerly orientations. Studies on the effect of the depth of the balcony in different parts of Greece (Loukou et al. 2014) showed that for the colder regions a South-facing balcony with depth 1.0-1.6 metres can save as much as 30% in annual loads, while depth above 1.9 metres can have a negative impact. Kimmo et al. (2010) and Tsichritzis (2014) studied the particular environmental attributes of glazed balconies showing that size, type (recessed or protruding), parapet and material properties of the balcony can have a substantial effect on the thermal comfort conditions achieved in the balcony space and the energy performance of the adjacent indoor spaces. Acknowledging that the attraction of a private outdoor space continues to be very high in Mediterranean climates, this paper presents the results of measurements on two similar balconies and adjacent spaces in the urban context of Thessaloniki, Greece (40°38'N , 22°55'E). The fieldwork was

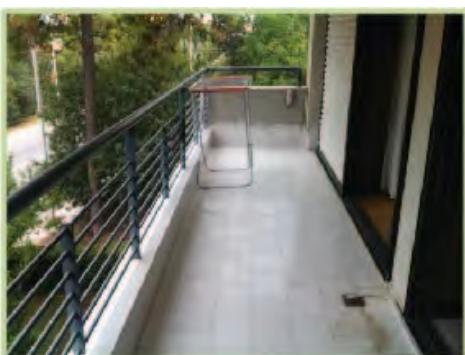
followed by simulation studies aimed at assessing the impact of different balcony typologies, the efficiency of different shading devices and variations in diurnal operational schedules.

## Fieldwork

Temperature dataloggers were installed over a period of two weeks in July 2016 in an unobstructed, detached 5-storey building to evaluate the effect of shading devices on the air temperature of the balcony and adjacent indoor spaces. Surface temperatures of the balcony floors were also recorded. The building is of conventional reinforced concrete construction with insulated brick and concrete block external walls, and aluminium frame double glazed windows and balcony doors. The balcony area (1.5m deep and 2.0-5.0m wide) had white marble floor, rendered white-coloured brick wall, light grey concrete parapet and/or steel railing.

Two neighbouring SW facing balconies (figure 1) were monitored for three consecutive days under similar weather conditions. Shading with a light-coloured awning was applied to Balcony A on all three days, and to Balcony B on the third day only. The adjacent rooms were unoccupied and the balcony doors kept closed with shutters applied to the adjacent room A1 and curtains to B (figure 2).

Higher air temperatures by up to 2K were recorded on balcony B compared to the more exposed neighbouring balcony A. Use of additional solar protection from awnings lowered the air temperature on the balcony by some 5K and the surface temperature of the balcony floor (white reflective marble) by 2K at peak time, as well as mitigated the indoor temperature at times of sun exposure. There was a small difference of 0.5K between the two balconies at night, which indicates that the lower Sky View Factor of balcony B due to the presence of awnings did not affect the heat dissipation rate.



Balcony A



Balcony B

Figure 1. View of the two neighbouring monitored balconies

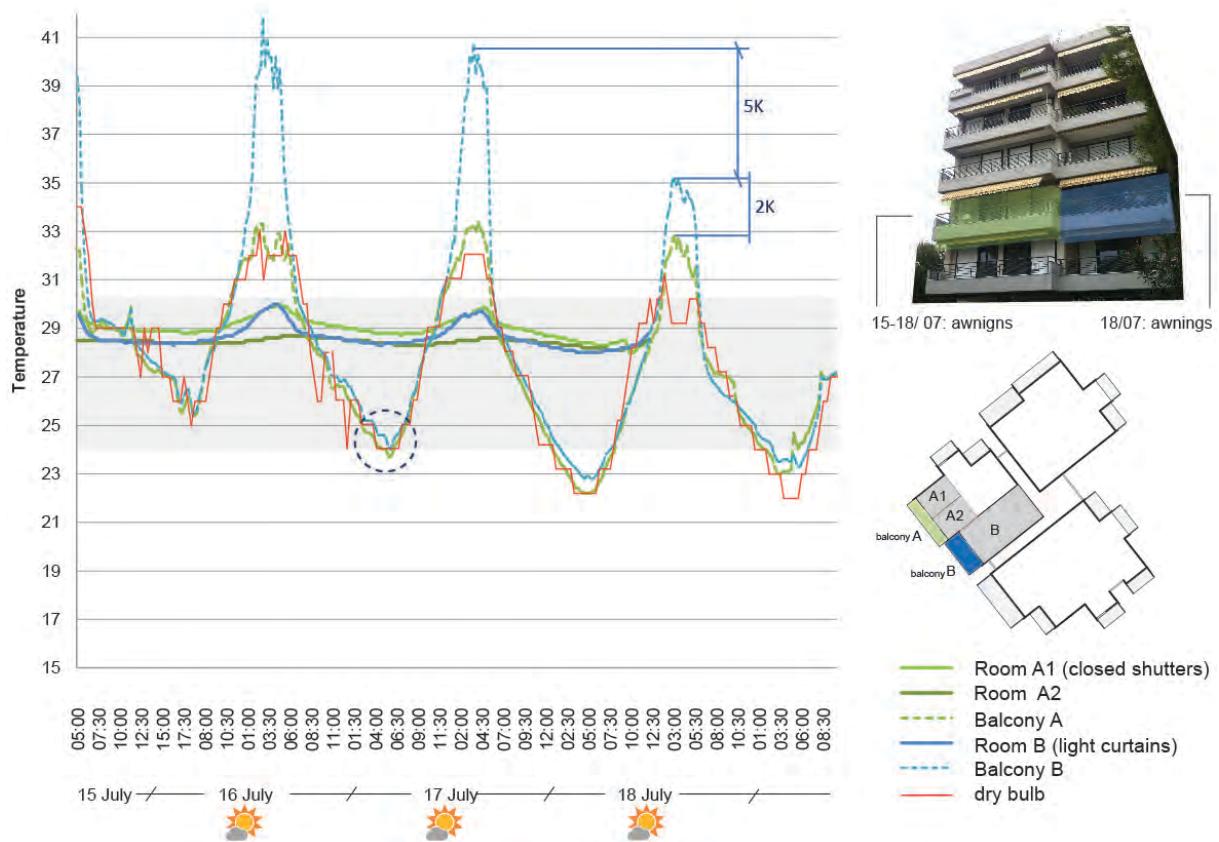


Figure 2. Air temperature readings during fieldwork experiments (15-18/07) in Thessaloniki

### Simulation Studies

Thermal simulations were performed with Energy Plus / Open Studio. Solar studies with Grasshopper / Ladybug followed from the fieldwork aiming to provide a deeper insight on the effect that the form and depth of the balcony, and awning operation might have on solar radiation entering the space. The building was modelled as a typical 5-storey residential structure of average height for the building stock in Thessaloniki (Theodoridou et al., 2011). The simulation studies focused on a rectangular room of 3.0m by 7.0m and 3m height located on the 4th floor, and its attached balcony of 1.5m in depth shaded by the overhang of the balcony of the floor above. The room has one external wall only with the other building elements modelled as adiabatic. The glazed door to the balcony is of 1.0m by 2.1m and double glazed ( $U=2.6 \text{ W/m}^2 \text{ K}$ ,  $g\text{-value}=0.44$ ) and the external wall insulated to  $U=0.5 \text{ W/m}^2 \text{ K}$ . All other thermophysical properties were modelled to conform with the requirements of the national building regulations controlling the energy performance of buildings (KENAK) for the climatic zone of Thessaloniki (T.O.T.E.E., 2010).

Three different balcony forms were studied, a fully protruding variant, a balcony with opaque parapet, and a recessed balcony with side walls and opaque parapet. These are shown in figure 3 and encompass the typology of residential balconies in Greece.



Figure 3. Main residential balcony types in Greece

Results for the worse case situations of a cloudy winter day and a sunny summer day are presented in figs 4 and 5. On cloudy winter days and nights the recessed balcony type is shown to develop slightly higher temperature, remaining 2K warmer than the outdoor air temperature throughout the day, probably due to its more protected form and thus reduced heat dissipation rate. In summer the side walls of this balcony block direct solar radiation resulting in lower air temperatures during the day but reduced heat dissipation during night-time. The simulated temperature differences are smaller than those measured and presented in figure 2.

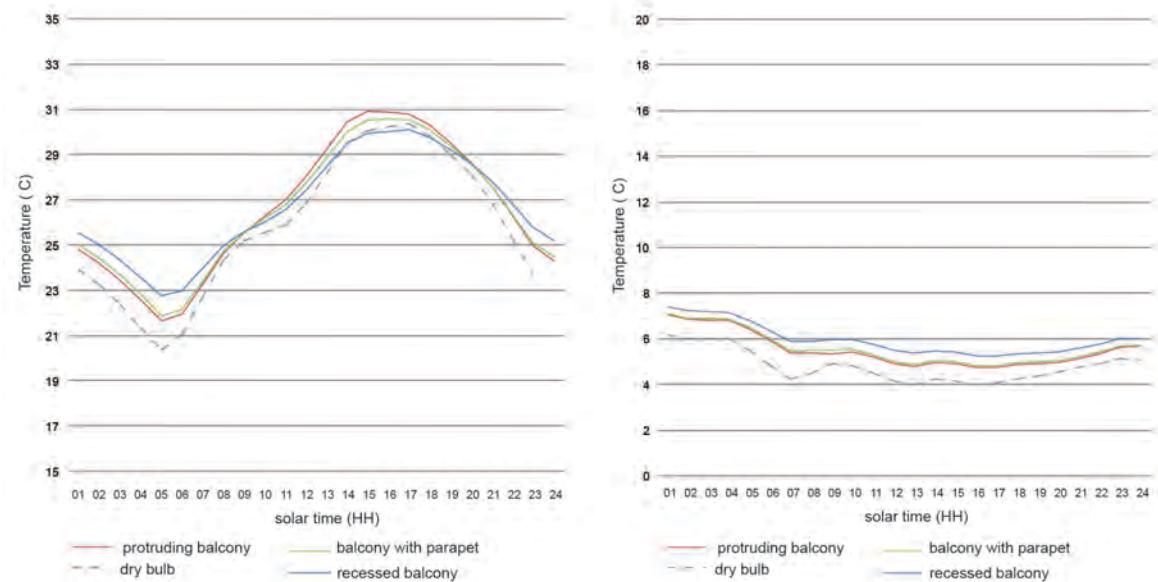


Figure 4. and 5. Diurnal temperature of three balcony types in a sunny summer day (left) and a cloudy winter day (right)

The effect the enclosure of the balcony may have on environmental conditions and occupant comfort is reflected on the levels of monthly total incident solar radiation on the balcony floor for June, as illustrated in figure 6. Due to the lower solar angle on West and East orientations, the opaque parapet partially shades the floor resulting in 50% reduction in incident solar radiation. Overall, due to the combined effects of the side walls and opaque parapet, the recessed typology delivers the best solar protection on all orientations; monthly total incident solar radiation on the balcony floor is reduced by 73% in the West/East orientation and by 48% in the South orientation. North-facing balconies are not

significantly exposed to the sun in the summer and thus any level of enclosure is not that relevant.

Figure 7 compares alternative shading configurations for the most critical orientations. Awnings provide effective solar protection on all orientations blocking all direct solar radiation on South-facing balconies. Horizontal louvers are almost as effective while also allowing airflow which can be instrumental for good summer operation, and providing improved privacy and views. Horizontal louvers show better results to vertical ones on all orientations. The depth of the shading device is instrumental in blocking high as well as low solar angles. Application of horizontal louvers on west-facing balconies can reduce air temperature by up to 6K in the balcony zone and by up to 1.6K in the adjacent indoor space (figure 8). This result is similar to that observed in the field measurements. A smaller reduction of 1K was found for the south-facing balcony. Figure 9 shows that not retracting the awnings at night has little effect on the balcony or indoors, as was the case with the fieldwork findings. Instead, in all the scenarios illustrated in the figure the temperature in the balcony remains 2K higher than the outdoor air indicating a slow rate of heat dissipation due to heat storage in the slabs.

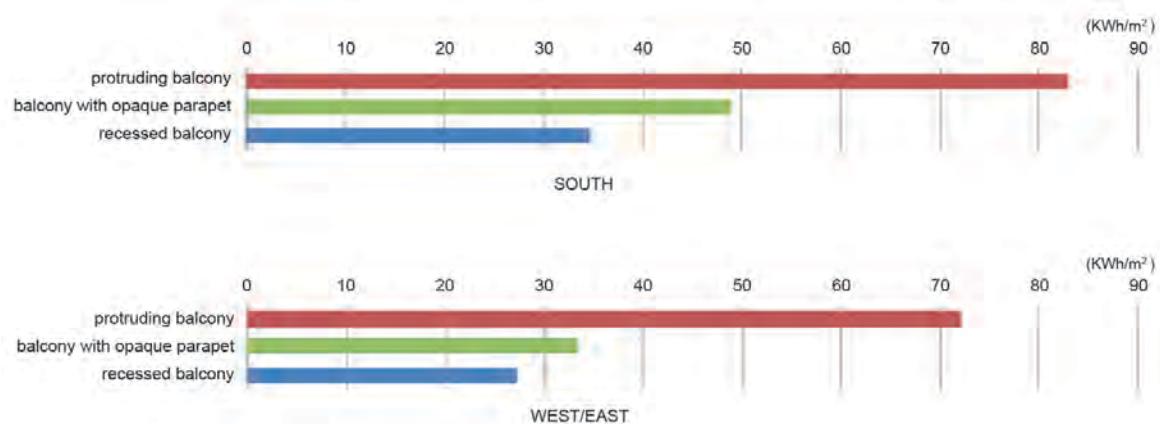


Figure 6. Monthly total incident solar radiation on balcony floor for June for the three balcony typologies

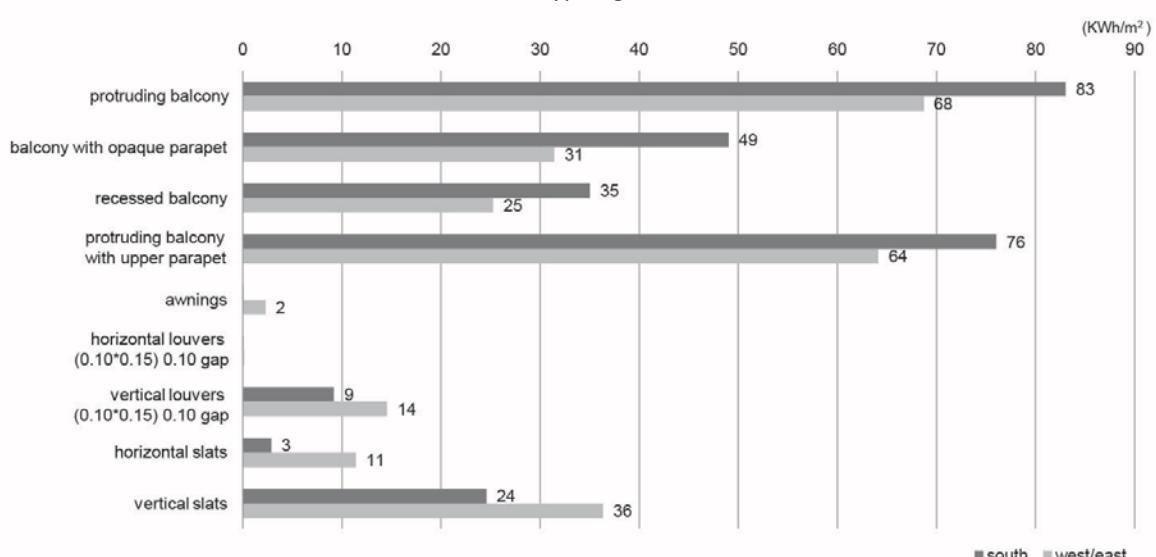


Figure 7. Monthly total incident solar radiation on balcony floor for June for different shading configurations in relation to the most critical orientations



Figure 8. Effect of solar protection on west-facing balcony and adjacent space on sunny summer day

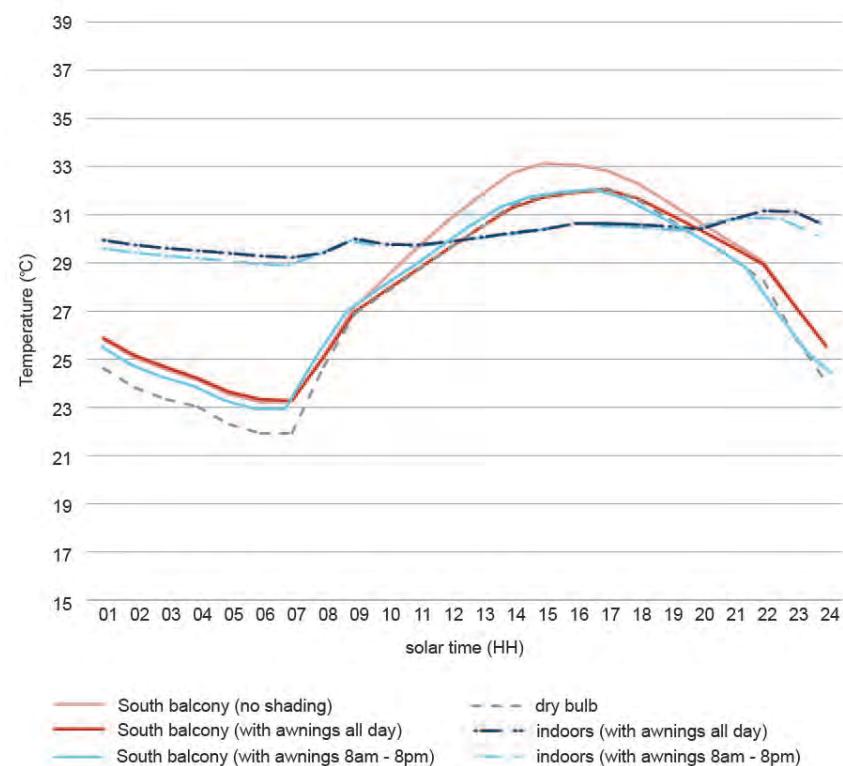


Figure 9. Effect of varying solar protection on south-facing balcony and adjacent space on sunny summer day

## Conclusions

Measurements and simulation studies have shown that balcony form and solar protection can significantly affect the thermal comfort of occupants on the balcony as well as in the adjacent space. Table 1 highlights the relative advantages and disadvantages of the main balcony types after evaluating the air temperature developed in the balcony zone for different weather scenarios. The table can function as reference for the design of the optimum balcony form in relation to diurnal and seasonal variations. It also indicates the high benefits of a balcony design which is adaptable to different weather scenarios. Table 2 summarises the findings of the simulations studies in the form of balcony design and solar protection recommendations. The application of adaptable systems functioning as shading devices or as night shutters may allow occupants to define the optimum levels of enclosure or solar protection of the balcony in an annual cycle. Applied to new or existing residential buildings, these design and operational recommendations can result in annual energy savings as well as extend the usability and functionality of the balcony over the annual cycle.

Table 1. Summary of the assessment of the balcony types in different weather scenarios.

Balcony cases	Winter season			Intermediate season			Summer season		
	sunny	cloudy	night	sunny	cloudy	night	sunny	cloudy	night
	✓✓	-	✗	✓✓	✓	-	✗	-	✓✓
	✓	-	✗	✓	✓	-	✓	-	✓
	✓	✓✓	✓✓	✓	✓	✓✓	✓✓	-	✗

✓ recommendable    ✓✓ acceptable    - indifferent    ✗ not recommendable

Table 2. Design and solar protection recommendations for the balcony zone

	sunny day	cloudy day	night
Winter Season			
Intermediate Season			
Summer Season			

## References

- Chan A.L.S., T.T.Chow (2010). Investigation on energy performance and energy payback period of application of balcony for residential apartment in Hong Kong, *Energy and Buildings*, 42, pp 2400–2405, Elsevier
- Florides G.A., Tassou S.A., Kalogirou S.A., Wrobel L.C. (2002). Measures used to lower building energy consumption and their cost effectiveness. *Applied Energy*, 73, pp 299-328, Elsevier
- Kimmo H., E. Mäkitalo, J. Lahdensivu, (2015). Energy saving potential of glazed space: Sensitivity analysis, *Energy and Buildings*, 99, pp 87–97, Elsevier
- Loukou E. , E. Skrafnaki and K. Tsikaloudaki (2014). Achieving solar shading with balconies: guidelines for optimal design for Greek residential buildings in: *12o International Conference: Protection and Restoration of the Environment*, proc. no 251 , 2014, Skiathos Greece
- Song D, Choi YJ. (2012). Effect of building regulation on energy consumption in residential buildings in Korea. *Renew Sustain Energy Rev*, 16, pp 1074-1081, Elsevier
- T.O.T.E.E (2010) Thermophysical properties of building materials and evaluation in *Technical Guidelines T.O.T.E.E. 20701-2/2010* (in Greek), Energy Performance of Buildings Directive, A edition, Athens
- Theodoridou I., A.M. Papadopoulos, M. Hegger(2011b) Statistical analysis of the Greek residential building stock. *Energy Buildings*, 43, pp. 2422-2428, Elsevier
- Tsichritzis L. (2014) *Passive Solar Retrofit in Athens: The Potential of Glazed Balconies*. MSc Dissertation, Architectural Association Graduate School, London



# PLEA 2017 EDINBURGH

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## The Improvement Potential on Building Performance Using Seasonal Adaptable Facades – The Context of Residential Buildings with High Thermal Load in Humid Subtropical Climates

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**Abstract:** Improvements in design, conception and construction of facades play an important role in promoting building energy efficiency. Climate adaptable building shells (CABS) can improve building thermal performance by modifying the envelope properties in response the dynamic environmental boundary conditions. This paper intends to evaluate the improvement potential of building thermal performance using seasonal adaptable facades in residential buildings with high thermal load in a humid subtropical climate. A case study is performed in south-eastern of Brazil, in order to identify the optimal seasonal adaptation strategies. The analysis is based on optimization scenarios. The numbers of overcooling and overheating hours are the indicators of performance. The adaptive comfort model, Thermal Environmental Conditions for Human Occupancy, bases the measurement of the comfortable hours. The optimization of the results is conducted using the software MatLab and the computational simulations are conducted using EnergyPlus. Results of this study show the improvement in environmental quality through monthly adaptation of six facade designs parameters. Separate analyses are made for the summer and the winter. The potential on thermal performance improvement in this case study reduced up to 26% of the discomfort time with the adaptive facade. Reducing the number discomfort hours reduces energy consumption by the use of cooling or heating systems.

**Keywords:** Climate adaptive buildings, seasonal facade adjustment, adaptive facade, building performance simulation, thermal comfort.

### Introduction

Architectural projects nowadays have become increasingly complex due to the growing demand for ambitious performance requirements of social, environmental and economic related issues. (Loonen et al. 2013).

Building envelope is the primary subsystem able to regulate external conditions and environmental changes and it is very relevant concerning sustainability in buildings (Barozzi et al. 2016). The facades are determinants for the internal environmental conditions (Lai & Hokoi 2015). Thermal, visual and mass-flow are some of physical domains of the envelope that can influence the indoor environment (Loonen et al. 2017).

Static building envelope systems limit the possibilities of energy performance and / or the generation of optimal internal comfort levels (Boer et al. 2011) as they do not respond

to the external changing weather conditions throughout the day and/or the year, nor to the variable needs of their occupants (Loonen et al. 2011).

The adaptive facade systems have the potential to reduce the emission of polluting gases, and improve the energy performance of buildings, maintaining high levels of quality of the internal environment. This is due to the dynamic nature and ability to adapt through materials, components or systems to different boundary conditions. With optimized performance, as one of its characteristics, adaptive facades can significantly contribute to meet ambitious energy conservation goals such as the European Union's energy conservation targets for 2020 and 2050 (Loonen et al. 2017; Aelenei et al. 2016; Goia et al. 2014; Loonen et al. 2015; Jin et al. 2015).

However, adaptive facade designs are challenging, since they are characterized as complex systems that simultaneously influence multiple physical domains, such as thermal and luminous conditions. The great technical potential of this type of envelop has been demonstrated in several types of international publications. The reduced number of applications of the techniques is partly due to the lack of understanding of its benefits, but also due to the high level of complexity during the design, construction and operation of the buildings (Kasinalis et al. 2014; Loonen et al. 2017).

While most work about adaptive facade has been focused on short term adaptation (e.g. hourly), there are studies that demonstrate the large potential of seasonal adaptive facades. For instance, a study conducted in office buildings in moderate climates showed a reduction in energy consumption up to 18% compared to the best performing static building facade (Kasinalis et al. 2014).

Given the potential of this dynamic facades and the reduced number of studies conducted in hot climates, the aim of this study is to evaluate the improvement potential of building thermal performance using seasonal adaptable facades in residential buildings with high thermal load in a humid subtropical climates.

## Methodology

The methodology adopted was divided into the following phases: definition of the cases to be studied; performing computational simulations by EnergyPlus through routines of automations written in MatLab; and analysis of results.

### Case study building model



Figure 1. Schematic overview of the investigated room zone model.

The zone under investigation is a room ( $l \times w \times h = 4\text{m} \times 3\text{m} \times 2.7\text{m}$ ) for two people (for all the day), having its main facade oriented to the south (Figure 1). The room is situated on an intermediate floor and surrounded by other rooms. The zone was evaluated under climatic conditions of a Brazilian city (Porto Alegre – RS).

Rooms with high levels of sealing should be represented by rates between 0.3 and 0.61 ACH, so a rate of 1 ACH represents a room with good sealing (Tommerup et al. 2007; Pereira & Ghisi 2008). Simulations were performed considering the zone infiltration

provided at rates of 1, 2, 4, 8 and 16 ACH for the whole day. Window to wall ratio (WWR), thermophysical and optical material properties are determined by optimization. The adaptable design parameters are given in Table 1 (Kasinalis et al. 2014).

Table 1. Range of design parameters.

Parameters	Range	Unit
Density ( $\rho$ )	50 - 3000	[kg/m <sup>3</sup> ]
Specific heat (cp)	0.8 – 1.2	[kj/(kg/K)]
Thermal conductivity ( $\lambda$ )	0.01 – 2.5	[W/(m.K)]
External surface absorptance ( $\alpha$ )	0.1 – 0.9	-
Window to wall ratio (WWR)	10 - 80	(%)
Glazing ID	1 - 7	-

Existing window systems were used in the analysis. Details about the properties of glazing types that correspond to the glazing IDs from Table 1, are present in Table 2. No external shading system is applied to control solar gains (the critical situation is analysed). Electric equipment has a total power of 80W.

Table 2. Glazing properties.

	Glazing ID						
	1	2	3	4	5	6	7
U-value[W/m <sup>2</sup> K]	5.7	2.8	1.4	1.4	1.3	1.3	0.9
g-value [-]	0.86	0.76	0.59	0.62	0.59	0.62	0.59

The final results are synthetized in order to extract the main results.

### Performance indicators

In this study, analyses were made for the months of January and August. The objective was the analyses of the months of the year considered as critical in Porto Alegre – RS. According to the simulations performed, January is the summer month with the highest number of overheating hours (hours of discomfort for heat) and August is the winter month with the highest number of overcooling hours (hours of discomfort for cold) inside the zone.

The number of discomfort hours in the zone in January and August measured the performance of the investigated cases. In order to analyse the most critical situation, the number of discomfort hours is calculated for 24 hours of the day.

The adaptive comfort model (ASHRAE Standard 55-2013 2013), “Thermal Environmental Conditions for Human Occupancy”, based the measurement of the comfortable hours. This study considered the set of operative temperatures limits with 80% of acceptability. For this case, the formula below, measures the upper and lower limits of the comfortable region.

Acceptable operative temperature ( $t_o$ ) ranges:

$$\text{Upper 80\% acceptability limit } ({}^\circ\text{C}) = 0.31 \overline{t_{pma(out)}} + 21.3 \quad (1)$$

$$\text{Lower 80\% acceptability limit } ({}^\circ\text{C}) = 0.31 \overline{t_{pma(out)}} + 14.3 \quad (2)$$

Where:

$t_o$  = The allowable indoor operative temperatures calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of zone inside surfaces.

$\overline{t_{pma(out)}}$  = Mean daily outdoor air temperature.

### ***Simulation and optimization strategy***

During simulations, a random choice using the Monte Carlo method leads simultaneous combinations of the six parameters analysed. Five hundred cases were simulated for each infiltration rate and based the analyses. This is in fact a brute force approach on optimization using a relatively small sample, therefore results can be considered as preliminary. Such preliminary results require less computational power than optimization using genetic algorithms and can be used to target efforts to cases where the potential gain is significant.

The base case geometry was made in SketchUp and imported to Energy Plus V8.6 using Legacy 1.6 plug-in. The optimization process was carried out using routines written in the software MatLab R2014a (Walsh et al. 2016). The results supported the analysis of the potential on building performances improvements using seasonal adaptable facades.

Simulations made for each month allow the investigation of the adaptation. Combination of January and August results determined a group performance. The objectives are the number of discomfort hours by overcooling and overheating inside the model.

### ***The optimum group performance***

The combination of monthly-optimized solutions enabled the identification of the optimum monthly performance. The two-month analysis allowed the formation of two different Pareto fronts with monthly-optimized solutions for each simulated use configuration. The best group performance of the room was achieved by combining the best monthly solutions of the analysed characters. Thus, the best group solutions were obtained from the sum of the optimal Pareto points identified for January and August.

### ***Analysis of de results***

Summarized results for simulations are presented through a comparison between the performances of the simulated cases for all the hours of the months of January and August (1488 hours). It is indicated the potential on building performances improvements using seasonal adaptable facades in residential buildings with high thermal load in a humid subtropical climates.

### ***Optimum performance of static facade***

Figure 2 shows the performance of the simulations carried out with the infiltration rates provided in 1, 2, 4, 8 and 16 ACH. The figure shows the performance of the room studied when the facade is static. In the figure are represented the hours of thermal discomfort for the months of August and January (vertical axis) according to the simulated cases (horizontal axis). Each point represents each of the five hundred different facade configurations simulated for each rate infiltration. The performance of each static facade configuration was obtained by the sum of the overcooling and overheating hours for each case. Through the figure, it is clear the influence exerted by the facade configuration and infiltration rate on the thermal performance of the analysed room.

In the figure, the range of thermal discomfort hours for the cases simulated is almost 42% and 91%. The static facade which presented the best performance was simulated with a zone infiltration rate of 8 ACH. The case simulated with this infiltration rate which presented the best performance presented almost 615 of thermal discomfort hours. High infiltration rates make indoor and outdoor environments alike and can cause discomfort for cold in winter, so most of the hours of discomfort is due to overcooling in August. In the summer month, no overcooling hours were identified in any of the simulated cases.

Small infiltration rates result in heat build-up in summer time. Thus, the poor performance of the simulated cases with a zone infiltration rate provided in 1 ACH is due to the accumulation of heat in the room in the summer days. For the small rate infiltration, almost 75% of the five hundred simulated cases presented discomfort for overheating at all hours of the day in January. It is important to note that this is the infiltration rate that presented the best case performance for the winter month.

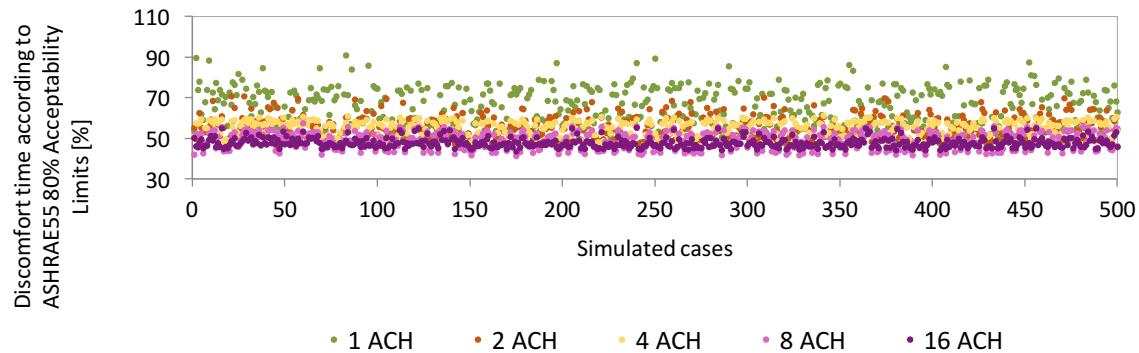


Figure 2. Static facades performance.

### **Performance of seasonal adaptive facade**

The identification of the Pareto fronts for January and August allowed the combination of the best solutions for the formation of adaptive facades. Figure 3 illustrates the performance of adaptive facades. All possible combinations of January and August Pareto fronts of each infiltration rate are shown in the figure 3. Each case represents the sum of the hours of overcooling and overheating for all possible cases of adaptive facades. The figure shows the cases on the horizontal axis, and the hours of discomfort for the two analysed months on the vertical axis. The red dotted line represents the performance of the best simulated case of static facade.

The figure shows that, as like in the static facade, the performance of the room also varied according to the properties of the adaptive facade and the infiltration rate provided in the room. It was observed that some adaptive facades simulated with infiltration rates provided in 1, 2, 4 and 16 ACH presented lower performance than the static facade with better performance identified. The cases that presented better performance were highlighted, according to the infiltration rate.

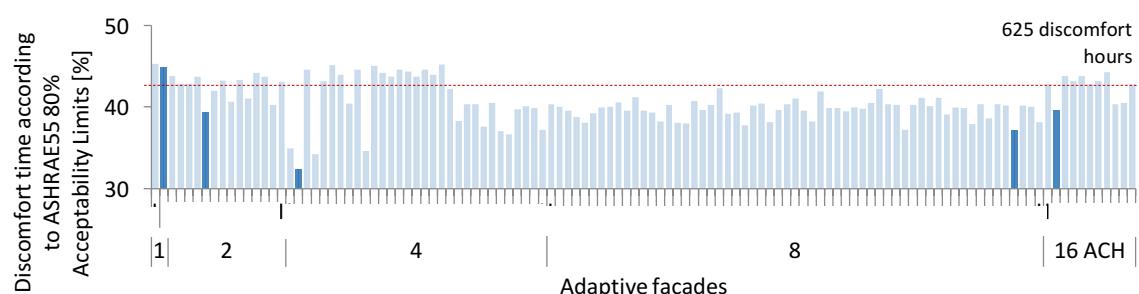


Figure 3. Adaptive facades performance.

Figure 4 (A) illustrates the comparison of the performance between static facades and adaptive facades simulated with the same infiltration rates. The best case identified for each

category simulated is presented. The cases are presented on the horizontal axis and on the vertical axis are presented the percentage of hours of thermal discomfort inside the room during the winter and summer months.

In the figure it is clear that the performance of the room with the adaptive facades is better for all the infiltration rates simulated. The best thermal performance with an adaptive facade was simulated with an infiltration rate provided in 4 ACH and achieved order to 26% reduction of discomfort hours. The potential reduction in hours of thermal discomfort varied from 8% to 18% in other infiltration rates.

Figure 4 (B) illustrates details of the performance of the room simulated with a rate infiltration provided in 4 ACH and best performance of adaptive facade. The figure shows that the room presented approximately 25% of the hours of thermal discomfort by heat. Approximately 92% of the overheating hours were in January and the other 8% were in August. The time of overcooling was approximately 7% and identified in the month of August, so there is no risk of discomfort for cold in the summer. During approximately 68% of the total hours of the winter and summer months the room did not present hours of discomfort according to ASHARE 55 - 80% Acceptability Limits.

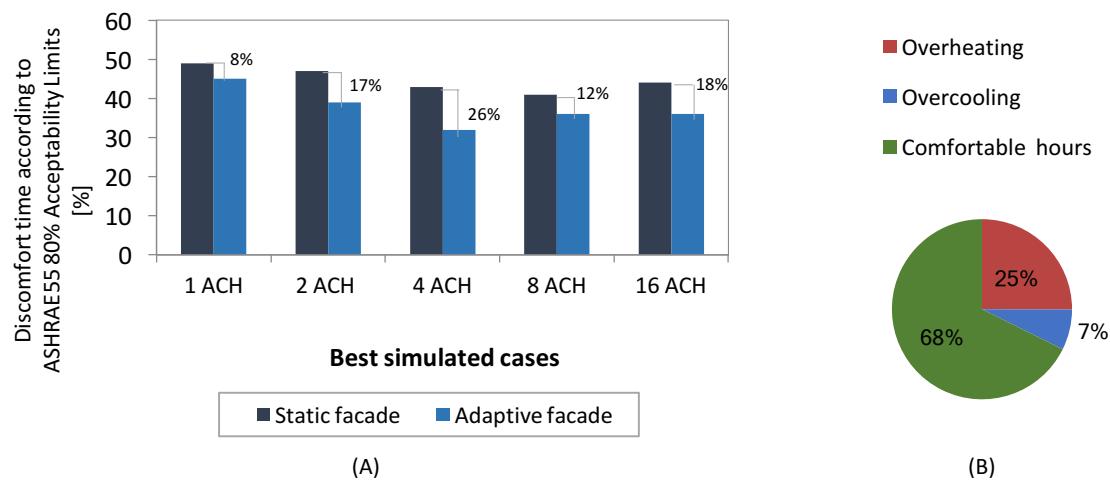
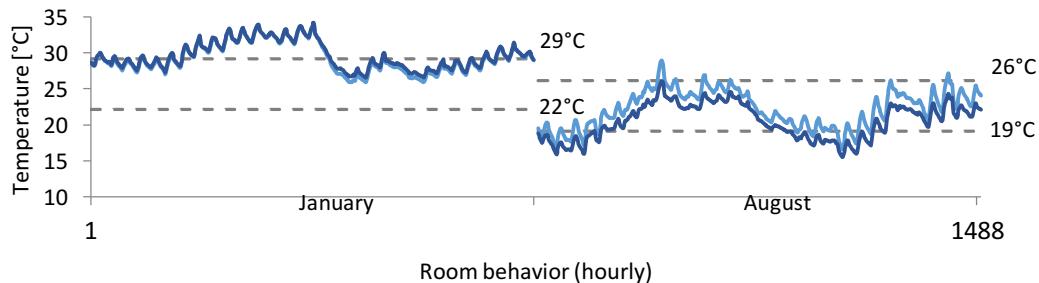


Figure 4. A)Thermal comfort improvement with different ACH rates and B) details of the best performance of the adaptive facade with 4 ACH.

### ***Optimum performance of seasonal adaptive facade***

Figure 5 presents the performance of the room for the static and adaptive facades which presented better performance simulated with an infiltration rate provided in 4 ACH. The figure shows a non-expressive level of attenuation in hours of heat discomfort through the use of adaptive facade in January. The improvement in hours of overheating was only around 1% (from 377 hours to 345 hours).

In January, the figure shows a notable difference between the performances of the room when compared the simulations with adaptive facade and static facade. The room with the static facade presented 256 hours of overcooling and no risk of overheating. Through the use of the adaptive facade there was a reduction in the hours of overcooling and the room started to present some hours of overheating. The improvement in total hours of thermal discomfort was almost 47% and the improvement in hours of overcooling was almost 58% (from 256 hours to 108 hours). The overheating hours, that came to exist with the adoption of the adaptive facade, totalized 28 hours.



— — — Comfort boundaries according ASHRAE Adaptive Model 80% Acceptability Status

— Best adaptive facade case (4 ACH)

— Best static facade case (4 ACH)

Figure 5. Room thermal conditions during January and August.

Table 3 allows a better understanding of the optimum design characteristics of best case scenarios using adaptive facades. Density and specific heat did not present a significant influence in thermal comfort inside the room.

Low thermal conductivity values decrease conductive thermic exchanges or the heat flux between the internal and the external environments. High thermal conductivity values are ideal for summer but can contribute to the overcooling in winter.

A higher external surface absorptance increases the solar gains, consequently during the summer it contributes to increase discomfort hours. Higher levels of solar absorptance are better during the winter.

The evolution of Glazing ID showed that a high-performance fenestration, low U-value (1.3 and 0.9 W/m<sup>2</sup>K) and low g-value (0.59), is important for summer and winter. Large windows contribute to the incidence of solar rays inside the room in winter. The glazing-ID and WWR rate are directly interconnected, and they influence the quality of the indoor environment.

Table 3. Best adaptive facade design parameters

Parameters	January	August	Unit
Density ( $\rho$ )	2710	2645	[kg/m <sup>3</sup> ]
Specific heat (cp)	1.19	1.19	[kj/(kg/K)]
Thermal conductivity ( $\lambda$ )	1.66	0.10	[W/(m.K)]
External surface absorptance ( $\alpha$ )	0.18	0.79	-
Window to wall ratio(WWR)	10.8	75.6	(%)
Glazing ID	5	7	-
Infiltration rate	4	4	ACH

## Conclusion

This paper showed the maximum potential of reduction in the hours of thermal discomfort by using an adaptive facade in the order of 26% for the studied case.

The results showed the direct influence exerted by the properties of the facade and the infiltration rate on the comfort levels inside the room. Depending on configuration of the facade and the infiltration rate, the number of overcooling or overheating hours can be higher or lower.

The adaptive facade for the studied room, with constant air infiltration rate, was more efficient in the improvement of thermal conditions in the winter.

For the analysed climate and studied case, the reduction in the number of overheating hours in the summer was not satisfactory. When the monthly performance was analysed, the room showed better performance in the month of January when simulated with 16 ACH. Studies of the potential on building performances improvements using seasonal adaptable facades with variation in infiltration rate in summer and winter should be performed.

Aiming to increase the efficiency (reduction of hours of discomfort) of residential adaptive facades in a humid subtropical climate, it is suggested that simulations and optimizations be performed for twelve months of year in future works.

## References

- Aelenei, D., Aelenei, L. & Vieira, C.P., 2016. Adaptive Façade: Concept, Applications, Research Questions. *Energy Procedia*, 91, pp.269–275.
- ASHRAE Standard 55-2013, 2013. *Thermal Environmental Conditions for Human Occupancy*,
- Barozzi, M. et al., 2016. The sustainability of adaptive envelopes: Developments of kinetic architecture. *Procedia Engineering*, 155, pp.275–284.
- Boer, B. De et al., 2011. Climate Adaptive Building Shells for the future – Optimization with an Inverse Modelling Approach. In *ECEEE Summer Study 2011*. Belambra Presquille de Giens: European Council for an Energy Efficient Economy, pp. 1413–1422.
- Goia, F. et al., 2014. Energy performance assessment of advanced integrated façades by means of synthetic metrics. In A. Li, Y. Zhu, & Y. Li, eds. *8th International Symposium on Heating, Ventilation and Air Conditioning*. pp. 21–28.
- Goia, F. et al., 2010. Towards an active, responsive, and solar building envelope. *Journal of Green Building*, 5(4), pp.121–136.
- Jin, Q., Favoino, F. & Overend, M., 2015. The potential opaque adaptive façades for office buildings in a temperate climate. In *Proceedings of Building Simulation 2015 Conference*. Hyderabad, India, pp. 98–105.
- Kasinalis, C. et al., 2014. Framework for assessing the performance potential of seasonally adaptable facades using multi-objective optimization. *Energy and Buildings*, 79, pp.106–113.
- Lai, C.-M. & Hokoi, S., 2015. Solar façades: A review. *Building and Environment*, 91, pp.152–165.
- Loonen, R.C.G.M. et al., 2013. Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25, pp.483–493.
- Loonen, R.C.G.M. et al., 2015. Design for façade adaptability – Towards a unified and systematic characterization. In *10th Conference on Advanced Building Skins*. Bern, Switzerland., pp. 1284–1294.
- Loonen, R.C.G.M. et al., 2017. Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation*, 10, pp.205–223.
- Loonen, R.C.G.M., Trcka, M. & Hensen, J.L.M., 2011. Exploring the potential of Climate Adaptive Building Shells. In *Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*. Sydney, pp. 2148–2155.
- Pereira, C.D.. & Ghisi, E., 2008. Calibração de um modelo computacional de uma residência unifamiliar localizada em Florianópolis. In *Planta*. Fortaleza - CE: ENTAC 2008 - XII Encontro Nacional de Tecnologia do Ambiente Construído.
- Tommerup, H., Rose, J. & Svendsen, S., 2007. Energy efficient houses built according to the energy performance requirements introduced in Denmark in 2006. *Energy and Buildings*, 39(10), pp.1123–1130.
- Walsh, A., Cóstola, D. & Labaki, L.C., 2016. Improving thermal comfort using cost-effective passive strategies. Lessons from a single-floor detached dwelling in Nicaragua. In *Proceedings of 9th Windsor Conference: Making Comfort Relevant*. Windsor, UK: Network for Comfort and Energy Use in Buildings (Ed.), pp. 7–10.
- Zhang, X. et al., 2015. Active Solar Thermal Facades (ASTFs): From concept, application to research questions. *Renewable and Sustainable Energy Reviews*, 50, pp.32–63.



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*Design to Thrive*

## Outdoor thermal comfort in a hot urban climate: analysing the impact of creating wind passageways in Al-Moski, Egypt using ENVI-met

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**Abstract:** Outdoor thermal comfort for pedestrians is difficult to achieve in high density, high population cities in hot climates, such as Cairo in Egypt. This study focussed on the outdoor thermal comfort of urban spaces in the Al-Moski district of Cairo and tested the effectiveness of creating new wind passageways at pedestrian level by selectively removing some of the buildings that encompass the Al-Moski area. The computational fluid dynamics (CFD) modelling software ENVI-met was used to create part of the existing Al-Moski urban form. Then, by extracting data from the CFD modelling, such as air temperature, wind speed, relative humidity and mean radiant temperature, the study was able to calculate the human thermal comfort index physiological equivalent temperature (PET). The urban form of Al-Moski was then changed in a systematic way by removing specific buildings in the ENVI-met model. The choice of building to remove was based on prevailing wind directions to see if accelerated flows at ground level through the newly created passageways could improve PET values. In addition, the benefit of adding areas of trees was also examined. The outcome of the analysis showed how a change in conditions, whether in the geometrical formation of the urban space or the addition of vegetation, could significantly affect the resulting PET values.

**Keywords:** wind passageways, outdoor thermal comfort, ENVI-met, simulation, PET.

### Introduction

Design driven by sustainability considerations is now adopted in many development projects, especially in architecture and urban planning, where one focus has been on increasing human thermal comfort. Though new projects have the potential to provide environmental friendly solutions, the existing building stock has the biggest impact on the environment. For example, it is estimated that 87% of current buildings in the UK will still exist by 2050, with a low rate of renewal of 1% annually (The Construction Products Association, 2009). With that being the case, retrofitting old buildings and managing existing urban spaces would have much bigger impacts on the environment and carbon emissions than new build.

The focus in this paper is derived from the need to improve the human comfort in the outdoor urban environment at pedestrian level by providing better urban spaces through modification of the local microclimate, especially in commercial areas of cities. The human body interacts with the environmental conditions around it, whether for indoor or outdoor conditions. The degree of comfort depends on the different factors that the built environment creates for its occupants, such as air temperature, wind speed and relative humidity. For that reason, choosing the appropriate approach is somewhat difficult due to the complex nature of the urban spaces, where the climate zone plays a very important role, as well as urban geometry, where the formation of the buildings can influence the climatic factors greatly.

Considering the above, this study investigated the possibility of improving outdoor thermal comfort in an urban commercial setting in Cairo, Egypt, by creating wind passages and adding vegetation. A comparative analysis between several proposed solutions was carried out by using ENVI-met, a three-dimensional CFD software that models and analyses the interaction between a selected location's microclimate and the local environmental conditions (ENVI-met, 2016). The model provided the study with the needed parameters, such as air temperature, wind speed, relative humidity and mean radiant temperature (MRT), to calculate the biometeorological comfort parameter the Physiological Equivalent Temperature (PET), which is the parameter used in the comparative analysis of different urban layouts.

## **Background**

### ***Context of study area***

Egypt is in North Africa and covers a land area of 1,001,450 km<sup>2</sup>. Egypt's capital is Cairo, with a population of 7.772 million. Cairo was chosen as the location for this study because it is a megacity with a hot arid climate. The aim was to identify an area in the city and to investigate, through ENVI-met CFD computer modelling, the impact that removing/demolishing existing buildings might have on thermal comfort by altering pedestrian-level wind flows to create new wind passageways. The Al-Moski district of Cairo was chosen as it contains a range of urban layouts with the potential for wind flow enhancement. The Al-Moski district of Cairo was founded by Izz El-Deen Mosk, in the reign of An-Nasir Salah ad-Din Yusuf ibn Ayyub founder of Ayyubid dynasty around 1160-1193. The district is famous for the old markets that combine different commercial products. The buildings in this area are influenced by the French architecture in the era of Ismail Basha, which along the years has been reoccupied and reused for multiple purposes (Al-Tarabili, 2003).

The area of Al-Moski chosen for the ENVI-met analysis is a commercial site in a hot arid zone with a very close, nearly random formation of buildings. Cairo lies in the warm desert climate zone, with dry summers and moderate winters (Peel, et al., 2007). The area has harsh winds twice a year, in spring and autumn, when sand and other impurities shroud the city for several weeks. Temperatures vary with the seasons, with values as high as 42°C in summer (June- August) with average mean temperature of 28°C, and temperatures as low as 6°C in winter (December- February). The average wind speed value in Egypt is around 3.5 m/s from the North to Northeast. However, the area experiences Al-Khamasin winds, which can reach 26 m/s in March and April, as well as in August and October.

### ***Thermal comfort***

Thermal comfort indices are based on energy balance models of the human body, and one of the most widely used models is Fanger's equation (Fanger, 1970), which was used to predict the indoor thermal comfort for air-conditioned spaces. The model was then adjusted by Jendritzky and Nübler (1981) to fit outdoor conditions. However, the model lacked realistic values of the thermal conditions of the individual's body, due the fundamental design of climate based equations not including all the human physiological conditions (Höppe, 1999). In 1984 Höppe introduced the Munich Energy-balance Model for Individuals "MEMI" that would consider human sweat rate, clothing surface temperature and core temperature. The MEMI is based on the heat balance equation following Büttner's work in the 1960s (Höppe, 1999).

Physiological equivalent temperature (PET) is a thermal comfort index introduced by Höppe and Mayer in 1987 which was based on MEMI (Höppe, 1999). Höppe (1999) defined PET as “*the physiological equivalent temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed.*” The typical indoor conditions that are referenced in the PET calculations are (Matzarakis et al,1999): 20°C air temperature, which is also equal to mean radiant temperature; 50% relative humidity and 0.1 m/s wind speed. In order to be able to calculate the PET, certain steps are needed (Höppe 1999):

- Setting the meteorological parameters to be used in MEMI to determine the individual's thermal conditions.
- Calculating the air temperature value through solving the energy balance equation with an individual's thermal parameters extracted from MEMI.

PET was the index of external thermal comfort adopted in this study and it can be calculated by ENVI-met. Table 1 shows how the PET thermal scale related to thermal perception and physiological stress.

Table 1: PET thermal scale

PET	Thermal perception	Grade of physiological stress
<4	Very cold	Extreme cold stress
4 to 8	Cold	Strong cold stress
8 to 13	Cool	Moderate cold stress
13 to 18	Slightly cool	Slight cold stress
18 to 23	Comfortable	No thermal stress
23 to 29	Slightly warm	Slight heat stress
29 to 35	Warm	Moderate heat stress
32 to 41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

## Method

Al-Moski is a commercial area with relatively high buildings ranging between 6m and 15m in height. The buildings are randomly placed with no inner streets and only pedestrian passageways, which greatly reduce the potential for natural ventilation in buildings. Figure 1 shows the existing urban layout as modelled in ENVI-met. Six receptors were positioned around the site (Figure 2), and these were the points where PET values were examined. Space constraints in this paper mean that not all the results from the six receptors can be presented. Considering Al-Moski's traditional nature, initial adjustments were proposed (Proposal 1) to eliminate three buildings, as seen in Figure 3, to create wind passages that would help in flushing out stale air and consequently raising the comfort level. Proposal 1 was put into simulation to see the effect of the minor adjustments, and the Receptors data were extracted for further comparison. Proposal 2 is a more invasive approach, eliminating more buildings to ensure more wind interaction inside the plot. And since the elimination process created more space, small scale vegetation areas were introduced in Proposal 2 to test out the effect the vegetation had in changing pedestrian human comfort levels (see Figure 4).

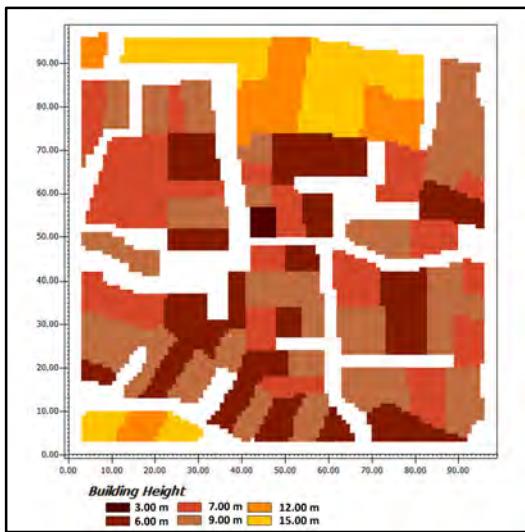


Figure 1. Building's height.

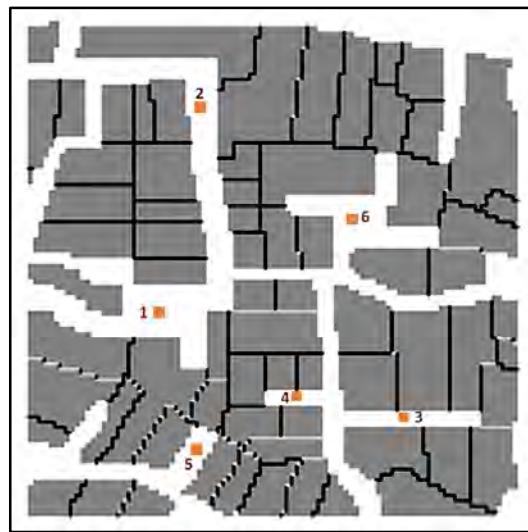


Figure 2. Existing Plot.

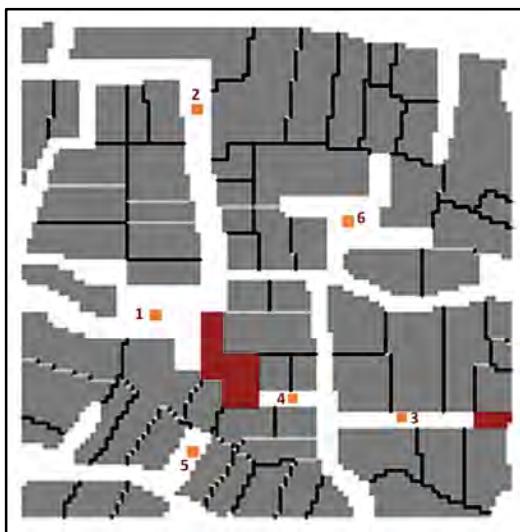


Figure 3. Proposal 1.

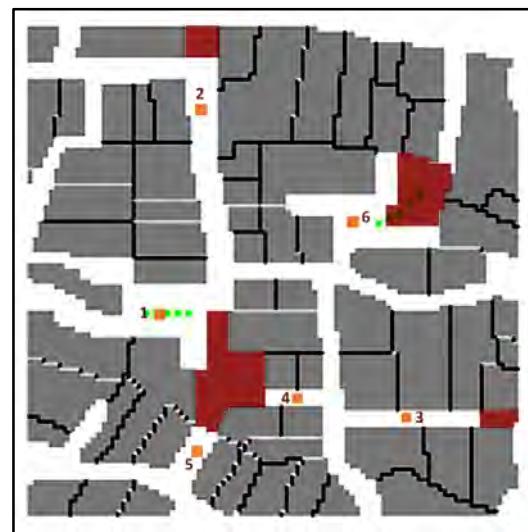


Figure 4. Proposal 2.

## Results and discussion

The PET levels for the existing area in summer time rise drastically when the sun irradiates the receptors, as shown in Figure 5. Differences in PET between the receptors are due to the different heights of the buildings surrounding each receptor, which will block the sun at different times of the day. The PET values patterns are, to some extent, similar for all the receptors except for receptor 2, which had lower PET levels. This can be explained by examining the initial climatic values (air temperature, wind speed, relative humidity and mean radiant temperature) for all the receptors. Although the difference in wind values is noticeable, the main reason for the low PET values for receptor 2 is the difference in received solar radiation. While the other receptors received solar radiation for more than five hours a day, receptor 2 only received two hours a day.

The PET levels for the existing area in winter, as shown in Figure 5, rise significantly for only in two receptors, 6 and 2. Due to the change of seasons the winter sun cannot reach all the receptors, resulting in PET levels ranging from cool to comfortable, excluding the two hours where receptors 2 and 6 receive direct solar radiation.

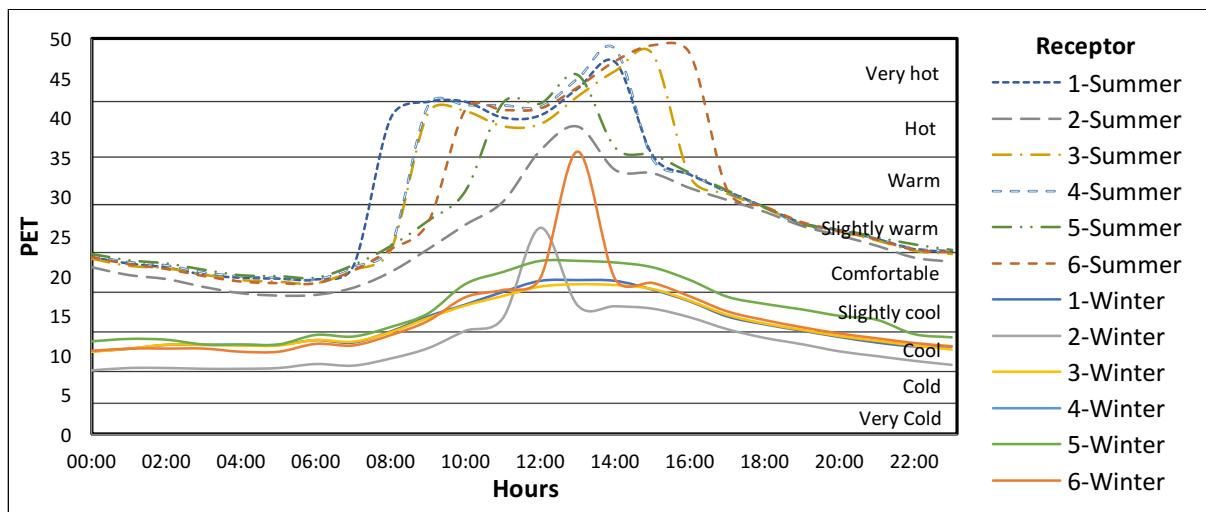


Figure 5. PET values for the existing plot – summer and winter.

### **Receptor 1**

Receptor 1 was in a relatively large square and the PET values in summer time exceeded the comfort levels, especially at noon. In Proposal 1 some buildings east of the receptor were removed to enhance the wind conditions, and no other major changes were made. In Proposal 2 the initial adjustments were kept, and a part of a building was removed to open a wind passage that was located north to the receptor. In addition to demolishing the building, a set of small sized trees were introduced to this receptor location since the space was wide enough for pedestrians' movement and landscape additions.

The wind speed values in the existing conditions were very low. With the adjustments to the existing site, a slight change in wind speed values can be noticed. However, the change was not more than 0.05 m/s for both Proposals 1 and 2. The improvement in PET values in Proposal 2, as shown in Figure 5, is due to the addition of vegetation, which introduced shading and cooler surfaces. The vegetation helped in reducing the mean radiant temperature  $T_{mrt}$ , thereby changing the PET levels. Although the  $T_{mrt}$  values were less than for the existing plot and Proposal 1, the air temperature remained the same with a maximum change in values of 0.35 °C.

The demolishing of certain buildings in Proposal 1 and 2 allowed the winter sun to reach receptor 1's location, which did not occur for the existing conditions. Other than that, no major changes in the PET values for Receptor 1 in winter were observed (see Figure 6).

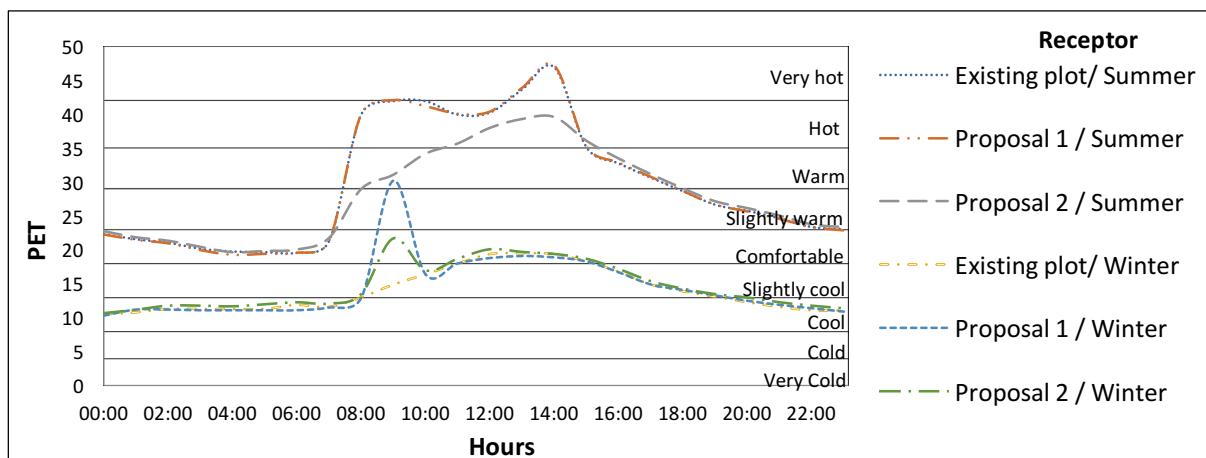


Figure 6. PET values for Receptor 1.

## **Receptor 2**

Receptor 2 was located at the end of a long street. The PET values for receptor 2 in summer time were very similar in the three scenarios. PET values behaved the same and peaked at noon when the sun was at its highest, resulting in hot values on the PET scale. For Proposal 1 there were no changes near the receptor and therefore the PET values graph is almost the same as for the existing site's PET values graph. However, in Proposal 2 a part of an existing building close to receptor 2 was removed to open a wind passage, and create a direct path through this commercial area that would link the two sides of the plot. Since there were no adjustments to the buildings close to receptor 2 in Proposal 1 the data extracted from the simulation did not change compared to the existing values. However, a significant change in wind speed of 1.9 m/s could be noticed in Proposal 2, due to the demolishing of the building to the north of receptor 2. However, there is not a large difference in the PET values, as seen in Figure 7. The increased values of wind speed helped in changing the air temperature, where it worked in two intervals throughout the day. It reduced the air temperature at night by flushing the hot air, and increased the air temperature by day by forcing hot air in.

PET levels did not change greater, especially when solar radiation was present, due to the greater effect that solar radiation has in the PET calculation, where it contributes more than the wind speed variable. Since the solar radiation levels were relatively high in the three scenarios, the PET levels did not show a noticeable improvement with the increased wind speed. However, during night time the PET levels in Proposal 2 were less than the other two scenarios as seen in Figure 7, due to the lack of solar exposure and increased wind speed.

As for the case of winter, the PET levels in Proposal 2 were lower than Proposal 1 (Figure 7), due to improved wind speed values. In this case the winter sun exposure impact on the PET levels was lower than summer time, which is why the wind speed effected the PET levels in winter and did not affect the PET levels in summer.

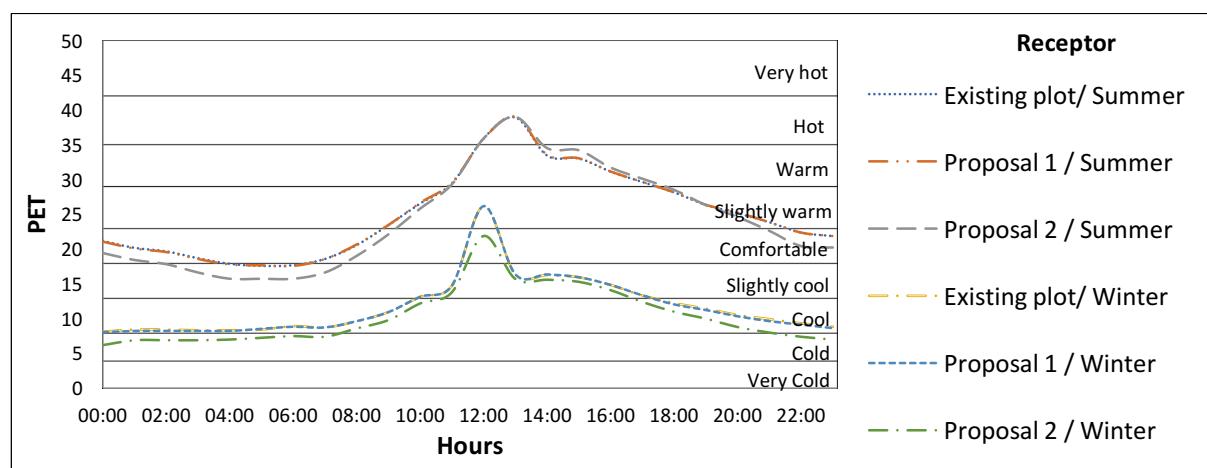


Figure 7. PET values for receptor 2.

## **Receptor 4**

Receptor 4 was in a small enclosed path. The PET values for receptor 4 in summer time were the highest compared to the other receptors - they exceeded the comfort levels, especially at noon, as shown in Figure 8. In Proposal 1 buildings to the west of the receptor were removed to enhance the wind conditions, and no other major changes were made. In Proposal 2 the initial adjustments were kept, and the building to the southwest of the receptor was removed to open a wind passage that was located near to receptor 5. The wind values in the three

cases were very low, ranging from 0.02 to 0.18 m/s; even with the demolition of the adjacent buildings that were blocking the wind flow, the values did not improve to a significant degree. The PET levels in Figure 7 show that the values in the three cases behaved in two intervals; the first interval was when there was not much solar radiation, which started at 17:00 and ended at 09:00. The PET levels in this interval were seemingly the same for all three cases, since the wind speed did not increase enough to influence PET values. The second interval started at 9:00 and ended at 17:00 when the solar radiation was present. Here it can be noticed that the PET levels for the existing plot have lower values than for Proposals 1 and 2, due to the demolishing of the buildings near the receptor that caused more solar radiation to reach that area. Figure 9 shows the shadows of the buildings at 15:00 for the three different cases, where receptor 4 is only shaded in the existing plot but not for Proposals 1 and 2.

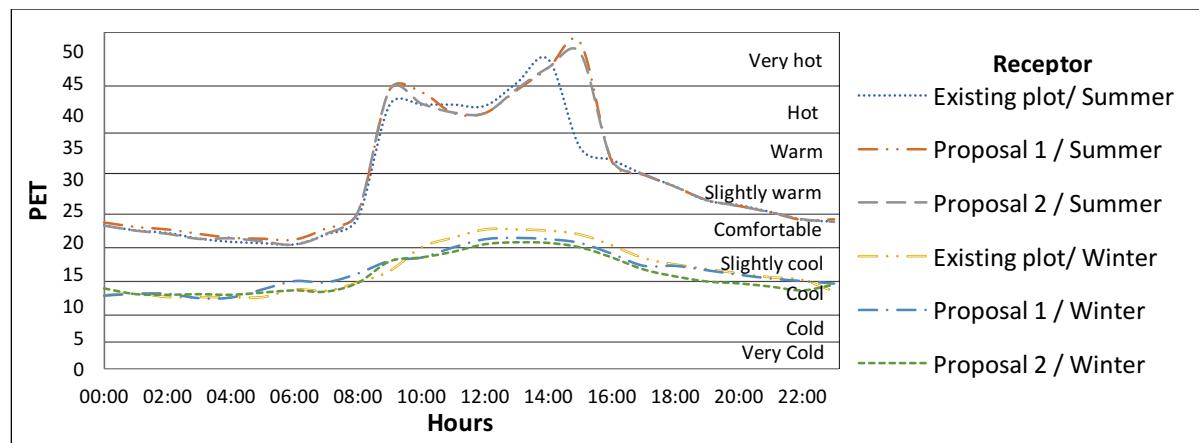


Figure 8: PET values for receptor 4.

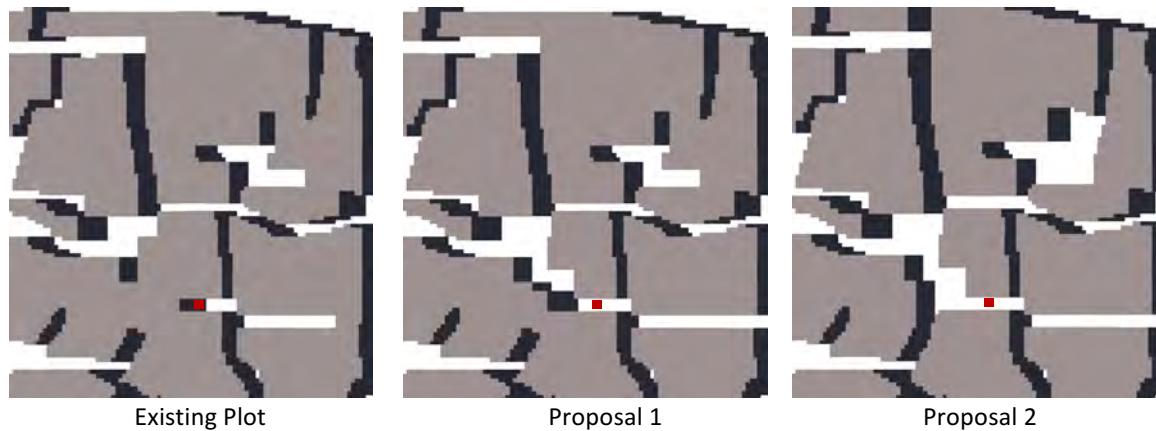


Figure 9. Shadows casts at 15:00.

As for the case of winter time, the PET levels in Proposal 1 and 2 were slightly lower than for the existing plot at 10:00 to 00:00, as seen in Figure 8, and relatively the same for the rest of the hours. This behaviour can be linked to the wind speed patterns, where Proposal 1 and 2 wind speed values are higher than for the existing plot at 10:00 to 00:00, and the rest of the hours have smaller differences in values resulting in almost similar PET values. Wind speed was still considerably low but in this case at winter, the receptor is overshadowed by the surrounding building all day.

## Conclusion

Choosing to demolish existing buildings to enhance an area's pedestrian microclimate is not a trivial consideration, and there could be conflicts between enhanced environmental sustainability, social sustainability and heritage issues. This paper has assessed the potential benefits of altering urban form as a mechanism for improving outdoor human comfort. From studying the results it is clear that PET values are influenced heavily by the climatic parameter mean radiant temperature Tmrt, and so creating shading, such as with vegetation, can significantly lower the values of Tmrt. However, there are certain conditions when the effect of the Tmrt has less impact on PET values - for instance, when the sun's position means a particular receptor is strongly irradiated. The findings from this study highlight that increasing local wind speeds at a site (by removing building obstructions) to try and lower a high PET value might not be effective if the removal means that the site is exposed to higher levels of solar radiation. Such findings can help in deciding the elements of future urban developments such as building geometry, street grids and shading devices.

## References

- Al-Tarabili, A. (2003). Ahya'a Al-qahera Al-mahrosa [The Guarded neighbourhood of Cairo]. 1st ed. Cairo: Al-Dar al-masriah al-lubnaniah, pp.70-99.
- ENVI-met, 2016. ENVI-met 4. A holistic Microclimate Modelling System. [Online] Available at: <http://www.model.envi-met.com/hg2e/doku.php?id=root:start> [Accessed 24 June 2016].
- Fanger, P.O., 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*, Danish Technical Press, Copenhagen.
- Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *Biometeorol*, Volume 43, p. 71–75.
- Jendritzky, G. & Nübler, W., 1981. A model analysing the urban thermal environment in physiologically significant terms. *Archives for Meteorology, Geophysics and Bioclimatology, Series B*, 29, 313-326
- Matzarakis, A., Mayer, H. & Iziomon, M. G., 1999. Applications of a universal thermal index: physiological equivalent temperature. s.l.:Int J Biometeorol.
- Peel, M. C., Finlayson, B. L. & McMahon, T. A., 2007. Updated world map of the Koppen-Geiger climate classification. *Hydrology and Earth System Sciences*, Volume 11, p. 1633–1644.
- The Construction Products Association, 2009. Memorandum submitted by the Construction Products Association. [Online] Available at: <http://www.publications.parliament.uk/pa/cm200809/cmselect/cmenvaud/202/202we06.htm>. [Accessed 24 March 2017].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A field study in southwest area of Spain: Thinking of thermal comfort and energy efficiency in existing buildings

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**Abstract:** The urgent need to decrease carbon emissions and the awareness of climate change leads to pay attention to energy demand in buildings. There is also an increasing concern with the perceived thermal comfort level of building's occupant. Therefore, suitable strategies are desirable to take advantage of the existing potential for energy savings in the indoor climate of a building, focusing on an improvement of the standard operating conditions of the heating, ventilating and air conditioning systems and looking for alternative criteria. Nevertheless a limited number of studies have taken place in Spain, and although there are outstanding researches within this field of study, continuing exploring the process of thermal comfort and the human being adaptation is always desirable. Consequently, a field study has been carried out in the southwest of Spain for several months in an educational building, involving monitoring environmental parameters and surveys.

**Keywords:** thermal comfort, energy efficiency, field study, HVAC

### Introduction

The concept of comfort has experienced an important transformation in the last years since while only three decades ago literature on indoor comfort was mainly focused on Indoor Air Quality (IAQ) nowadays buildings' users have greater expectations. Users expect comfortable indoor environments.

The research community on thermal comfort has grown substantially in recent years driven by policies designed to mitigate climate change and enhance energy efficiency. These policies require action by all players to make progress. The set of actions involve the urgency of decarbonizing the environment, the strategies to mitigate the greenhouse effect and other actions to improve energy efficiency, which have been contemplated in international protocols around the world. Initially, the Montreal protocol on substances that depleted the ozone layer in the late 1980s forced the HVAC sector to develop alternative refrigerants and subsequently the movement of green buildings imposed a fundamental rethinking of HVAC systems (de Dear et al, 2013).

The Directive 2012/27/EU of the European Parliament and of the Council underlines "*the increased dependence on energy imports and scarce energy resources and the need to limit climate change*", considering energy efficiency the best way to achieve it. The European Council stresses the need, and it is reflected in the previous directive, to increase energy efficiency in the Union in order to achieve 20% savings in energy consumption by 2020 compared to expected values.

The requirements of the users are becoming more demanding and the thermal well-being has acquired an increasing importance as it has a close relation with their productivity, their effectiveness and even their health. Nowadays, fixing a standard temperature key is not an efficient alternative and although the heating, ventilating and air conditioning systems (HVAC) usually have a control node, the information available to these systems to modify their operating conditions is very limited. They usually follow a standard law that has not been previously validated so it is usual that the degree of satisfaction of building's users with thermal conditions and indoor air quality is low.

Fixing indoor temperature based on needs of users would lead to an improvement in their comfort and would allow avoiding a waste of energy due to fixed values.

As buildings and their models play an essential role, attention to energy demand in buildings is increasing.

There are several studies which, based on adaptive theory, have emphasized the optimal comfort temperature inside buildings.

One of its main contributions is the ASHRAE model (ASHRAE 2013), and the SCATs project (Smart Controls and Thermal Comfort) (Nicol et al. 2012) carried out in 2010. After the SCATs, similar works have taken place in different climatic regions and different buildings.

Conceição et al. developed an adaptive model to evaluate thermal comfort in a kindergarten, both in winter and summer period, in the south of Portugal characterized by a Mediterranean climate. In Northern Italy, Fabbri collected surveys of children aged between 4-5 years old and Yun et al. proposed a new PMV model for children based on a field study carried out in Seoul. Different studies have taken place in university buildings in China, India, Malaysia, and Brazil. Hwang et al. carried out field studies in 10 FR classrooms and 26 AC classrooms at seven universities in Taiwan. In office buildings, Deuble and de Dear analyzed the thermal comfort in two office buildings at Sidney University, one of them operating in free-running and another in hybrid mode. In residential buildings, Becker and Paciuk analysed houses in Israel with and without HVAC system during winter and summer season. Inraganti's studies in apartments in India analyzed the difference between PMV-TSV. Moreover, in order to verify the applicability of the adaptive model in hybrid buildings several studies have been carried out in Shenzhen (subtropical climate), China and Melbourne and Sydney, Australia among others (Forgiarini et al, 2015).

Although outstanding field studies on thermal comfort have taken place, it is still advisable continuing this line of research to enhance and to further explore the adaptive process and thermal comfort. Such analysis could contribute to the improvement of comfort temperature decision makers.

In Spain, few several references for field study were found out. So in order to investigate the comfort range in the southwest region of Spain, a field study has been carried out, involving environmental variables and thermal sensation of users in an office building in Seville from October 2016 to January 2017.

## **Field study**

### **Climatology**

The world climate classification, based on the work of Köppen-Geiger, is still used. It identifies each type of climate with a series of letters (Kottek & Rubel, 2006).

Seville is located in the Southwest area of Spain, categorized according to the climatic classification of Köppen-Geiger in the group of temperate climates (type C). The climate in Seville is characterized by humid and not very cold winters with variable rainfall (when more than half of the annual rain is concentrated) and by dry and very hot summers when temperatures up to 40°C. In such period, one of the highest average temperatures in Europe can be observed.

Figure 1 shows the monthly evolution of the average minimum and maximum temperatures during a year (2016).

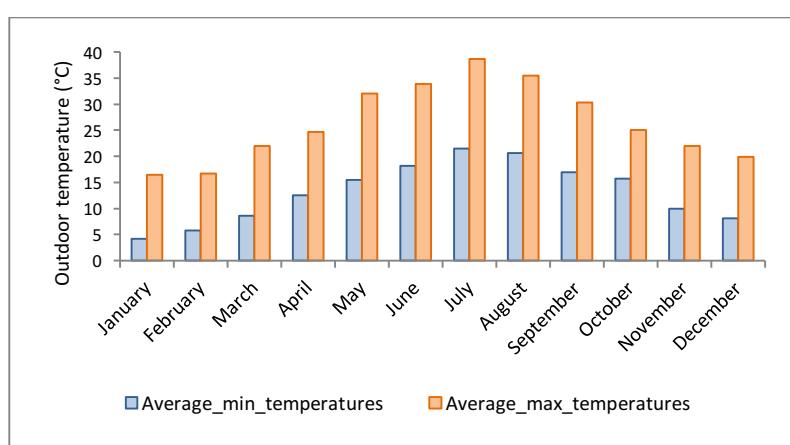


Figure 1. Seville outdoor temperatures.

### **The case study**

The field study has been carried out in a non-residential building. The room selected in that building to develop the field study was a 30 m<sup>2</sup> open office with four workers (two women and two men) located on a middle floor with SE orientation.

The office room has three double-glazed windows 87x139 cm, 87x139 cm and 184x139 cm sized respectively, a 40 cm outside brick wall and rolling shutters that can be controlled by users. It also has two fan-coils for air conditioning/heating with a set-point temperature. Users can control the on/off mode of the fan coils and they can set the temperature in the room (+/- 3 degrees based on the set-point temperature).

There are no pre-established dress codes, nobody has control on users' clothing, so they select the clothing to wear at any time.

### **Development of instrumentation**

The selected environmental variables were air temperature, relative humidity, air velocity, globe temperature, CO<sub>2</sub>, luminosity and surface temperature (Figure 2).

The first three variables are monitored because are required in most common comfort indexes (McCartney & Nicol, 2002). Since comfort may be relate with other environmental factors, variables related to indoor air quality and lighting are also monitored to find out possible interactions between these and the level of comfort perceived by users. The globe thermometer is a good predictor of the combined effect of air temperature, long-wave

radiation and air movement on human heat stress. Previous works highlight the feasibility of using a black globe thermometer with 40 mm diameter (Aparicio et al, 2016).

For the location of the sensors, the recommendations of the UNE EN ISO 7726 were followed. This standard advises that the variables related to indoor thermal environment should be measured in a representative sample of locations where the occupants spend their time and/or in the locations where the most extreme values of the thermal parameters are observed.

The sampling frequency of all sensors was uninterrupted for 15 minutes.



Figure 2. Sensors installed in the office.

### ***Thermal comfort surveys***

The thermal comfort perceived by users (temperature preferences, personal and emotional evaluations) are collected through surveys designed for this purpose based on the UNE EN ISO 15251 standard.

A daily survey (mainly for thermal sensation) and two additional questionnaires (weekly) on weekly clothing and satisfaction with other environmental factors such as the level of luminosity or smell in the room have been designed.

The thermal sensation and thermal preference of users were considered in the daily survey. The ASHRAE seven-point scale is used to assess thermal sensation, Nicol's five-point scale for thermal preference as well as a two-level scale for assessing overall acceptance of the thermal environment. The translation of the scales into Spanish is based on the UNE EN ISO 15251 standard.

### ***Technology***

The field study is characterized by the automation in the storage of the data. The system allowed storing the environmental variables, the comfort surveys and the HVAC system state.

Most of the previous studies required manual data collection, so the studies relied on the presence of the researchers, and in many cases, the sensors used for the monitoring of the environmental variables had a limited internal memory and it had to be released with a certain periodicity.

The present study establish the automation of the variables in the study and this automation makes easier the treatment of the volume of data, also reducing errors derived from the manual transcription of the data.

In addition, periodically processes have been carried out to check the state of the sensors, calibration and the surveys in order to identify and remove possible errors.

The surveys were filled in through a web page (PHP language) developed for this purpose. The system uses an Apache server. The data is stored in a database (MySQL). To fill in the surveys users should first register (editing their personal information: gender, age, etc.). After the registration, users could complete the surveys, showing the web page the questionnaires depending on the day of the week.

The structure of the survey included a list of questions with radio buttons for answering.

The data of the systems and sensors were also stored in the server, which allowed crossing the whole information, including outdoor data from a meteorological station.

## Results

It has been carried out a previous treatment of the data that make the subsequent analysis easier using Matlab. The programming routines carried out have allowed to identify in an automated way the periods in which the room was heated, based on the operation of the HVAC system, and to categorize the surveys depending if the building was in the free-running mode (with no heating) or not.

### **Distribution of variables**

Table 1 shows the mean and the standard deviation for inside variables which have been monitored during the studio (Ta: air temperature, Tg: globe temperature, RH: relative humidity, Va: air velocity) as well as the daily mean outside temperature (Tod). These values are separated taking into account that: if heating was in use, the data were classified as being in the heating mode (HT). If it was not, the data were classified in the free-running mode (FR).

Table 1. Inside and outside variables.

Building	Mode	Var	Ta [°C]	Tg [°C]	RH [%]	Va [m/s]	Tod [°C]
Office	FR	Mean	21.16	21.24	48.87	0.027	13.44
		S.D.	2.23	2.11	8.40	0.031	3.92
	HT	Mean	21.23	21.34	47.26	0.034	11.85
		S.D.	2.08	2.01	7.52	0.029	2.65

The mean outdoor temperatures during the surveys were 13.44 °C and 11.85 °C for FR and HT mode respectively. The mean globe temperature range between 21.24 °C and 21.34 °C for each mode. As shown in Figure 3 and Table 2 the globe temperature is highly correlated with the indoor air temperature (R-squared column), so globe temperature could be considered as a good index to analyse the data.

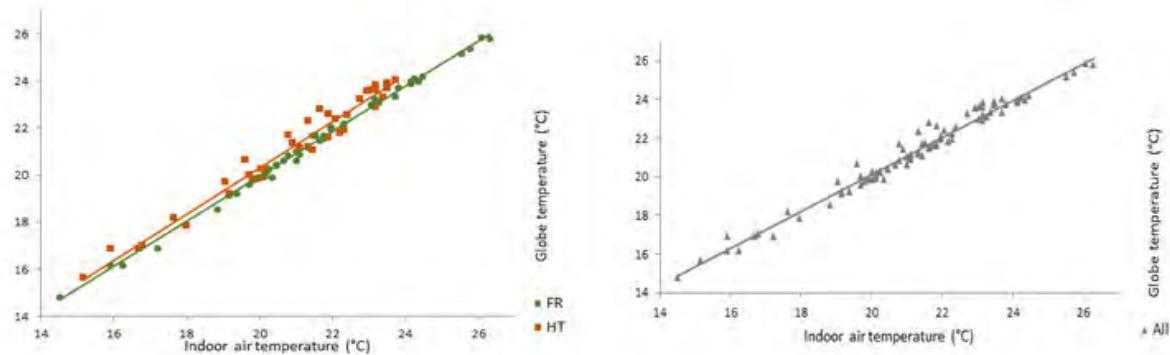


Figure 3. Indoor and globe temperature for each mode.

Table 2. Equations and correlation coefficients for globe and air temperature.

Mode	Tg-Ta	
	Equation	R-squared
FR	0.9569Ta+0.8163	0.99
HT	0.9812Ta+0.6859	0.97
All	0.9567Ta+0.9782	0.98

### Distribution of thermal sensation votes

From the surveys, the mean thermal sensation vote (Table 3) was -0.48 for the free-running mode and -0.45 for the heating mode (considering ASHRAE scale between -3 and 3). The mean thermal ranged from 0.53 (free-running mode) to 0.57 (heating mode). The Nicol's preference scale was used during the voting period (from -2 to 2). The whole distribution of thermal sensation votes is shown in Table 4, highlighting that sometimes people felt cold (less or equal than -2) or even hot (more or equal than 2) in the heating mode.

Table 3. Mean values of thermal sensation votes and thermal preference.

Mode	Var.	TSV	TP
FR	Mean	-0.48	0.53
	S.D.	1.14	0.68
HT	Mean	-0.45	0.57
	S.D.	1.37	0.86

However and despite the distribution of the votes it could be said that the vast majority of people was satisfied with their inside thermal environment. Most studies consider the comfortable range varying between -1 and 1 and taking into account all that values, the added percentage is about 70 per cent in the heating mode. Moreover, the number of neutral votes (votes equal to zero) is also high.

Table 4. Distribution of thermal sensation votes.

TSV	-3	-2	-1	0	1	2	3	All
FR (N)	2	25	44	27	32	2	0	132
FR (%)	1.52%	18.94%	33.33%	20.45%	24.24%	1.52%	0.00%	100.00%
HT (N)	7	37	41	29	39	10	1	164
HT (%)	4.27%	22.56%	25.00%	17.68%	23.78%	6.10%	0.61%	100.00%

### **Comfort temperature**

The comfort temperature is predicted by the Griffith's method (Table 5), based on the globe temperature and the thermal sensation votes, and using values for the Griffith constant (G) of 0.25, 0.33 and 0.50 (Rijal et al, 2017).

Table 5. Comfort temperature.

Comfort temperature		G=0.25	G=0.33	G=0.50
FR	Mean	22.83	22.56	22.03
	S.D.	3.89	3.22	2.08
HT	Mean	23.07	22.78	22.20
	S.D.	4.31	3.46	1.93

The mean comfort temperature is 22 °C and 22.2 °C in FR and HT modes respectively, being the mean comfort temperatures similar (G=0.25, G=0.33 and G=0.50). Figure 4 shows the relation between the comfort temperature (G=0.5) for the free-running mode and the running mean outdoor temperature ( $T_{rm}$ ) (Fergus & Humphreys, 2010).

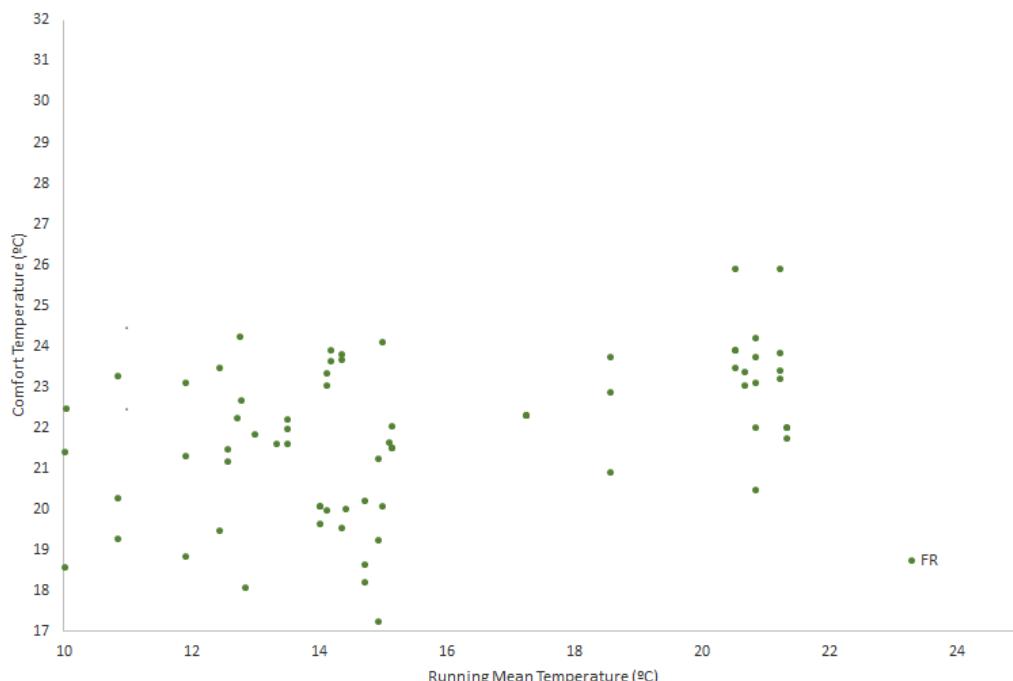


Figure 4. Relation between indoor comfort temperature and outdoor temperature.

Although the scatter of the votes, there is an important amount of them inside the comfort range (+/- 2K) established by the CEN standard for FR buildings,  $T_{comfort}=0.33T_{rm}+18.8$ .

### **Conclusions**

The following results are highlighted after analysing the data from the field study. Most occupants were satisfied with their office environment, based on the mean values of thermal sensation and thermal preferences votes and the distribution of the TSV. There was also a high number of neutral votes and higher amount of comfortable votes.

The mean comfort temperature is about 22 °C for all modes, being this values really similar using different valued for Griffith constant. Moreover, calculating the comfort temperature with the Griffith's method ( $G=0.5$ ) and the running mean air temperature there is an important amount of comfortable votes inside the range established by the CEN standard.

However, the relation between indoor comfort temperature and outdoor temperature should be further investigated considering a longer period of time and a higher number of buildings and occupants.

## References

- Aparicio, P., Salmerón, J. M., Ruiz, Á., Sánchez, F. J., & Brotas, L. (2016). The globe thermometer in comfort and environmental studies in buildings. *Revista de la Construcción*, 15(3), 57-66.
- ASHRAE, 2013. Standard 55-2013: Thermal environmental conditions for human occupancy R. and A. conditioning E. American Society of Heating, ed.
- De Dear R. J., et al. (2013) Progress in thermal comfort research over the last twenty years. *Indoor Air*, 23(6), p. 442-461.
- Directive 2012/27/UE of the European Parliament and of the Council of 25 October 2012 on energy efficiency.
- Fergus, N., Humphreys, M. (2010) Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, 45 (1), p. 11-17.
- Forgiarini Rupp, R., Giraldo Vásquez, N., Lamberts, R. (2015).A review of human thermal comfort in the built environment. *Energy and Buildings*, 105, pp. 178-205.
- Kottek, M. & Rubel, F., 2006. World Map of the Köppen-Geiger Climate Classification Updated. University of Veterinary Medicine Vienna. Available at: <http://koeppen-geiger.vu-wien.ac.at/present.htm>.
- Nicol, F., Humphreys, M.A. & Roaf, S., 2012. Adaptive thermal comfort: principles and practice, Routledge New York. Available at: <http://dx.doi.org/10.4324/9780203123010>.
- McCartney, K. J., Nicol, F. J. (2002) Developing an adaptive control algorithm for Europe. *Energy and Buildings*, 34(6), pp. 623-635.
- Rijal, H. B., Humphreys, M. A., & Nicol, J. F. (2017). Towards an adaptive model for thermal comfort in Japanese offices. *Building Research & Information*, 0(0), pp. 1-13.
- UNE-EN 15251:2008 Indoor environmental inputs parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
- UNE-EN 7726 Ergonomics of the thermal environment -- Instruments for measuring physical quantities.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Exploring alternative solutions for the alleviation of energy poverty: the thermal refuge study case in Pamplona (North of Spain)**

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**Abstract:** The aim of this paper is to present the case study of a low cost interior retrofitting intervention, a thermal refuge carried out in collaboration with Social Services and volunteers of the University of Navarra Tantaka Charity Group for a family in extreme poverty living in a cold dwelling from the 1970s in Pamplona (north of Spain). It presents a meaningful case of extreme energy poverty and its evidence from monitoring. Also defines the measures adopted to improve their indoor environmental conditions and exposes the main results of its efficacy from monitoring, infrared images and families comfort perception. Regarding the measures adopted two main sets of strategies were defined to improve the thermal conditions and comfort perception of the dwelling, on the one hand, reducing as possible the energy losses of the dwelling and reducing the impact of cold surfaces on operative temperature, and in the other hand, improving control, knowledge and habits of the householders in order to improve their adaptive thermal strategies and resulting perception of comfort at lower temperatures. Results demonstrate that the measures applied had a positive impact on temperatures and comfort perception and highlight the importance of exploring the opportunities and limitations of alternative intervention strategies.

**Keywords:** Energy poverty, Low income households, Indoor environmental quality, Low cost solutions

### **Introduction**

According to the EU SILC, living conditions survey in Spain, there is an 11% of the population that declared “being unable to keep their dwellings at an adequate level of warmth” during winter months. Among other impacts in human wellbeing -mental health, social attainment, stigmatization-, inappropriate indoor comfort levels has a very negative effect on health and results in a significant increase of the seasonal mortality and morbidity (Bouzarovski, 2011). Linkages between energy poverty and poverty suggest (Papada et al, 2016) (Santamouris et al, 2014) that low income families are more likely to suffer from more inadequate indoor conditions at home and become a crucial target group. This is due not only to their economical constraints to afford higher levels of energy services at home, but also due to the strong relation between poverty and poorer energy efficiency (Kolokotsa et al, 2015), inadequate heating systems, less economical resources, cultural and educational barriers, less access to credit and thereby reduced access to more efficient systems or fabric retrofits (Ugarte, S et all, 2016). Considering this set of pitfalls, low income families become a main target group with particular needs in the design of effective intervention guidelines for the provision of comfort in our society.

For this reason, not only political and financial support and economical incentives must be given to promote actions against this impact in Spain, but also developing and

providing alternative feasible retrofitting solutions that imply not only less cost, and less barriers, but also an effective provision of comfort at an affordable cost are needed.

In this paper is explored the validity of an alternative way of intervening in vulnerable families comfort at a reduced cost that could be a temporal an effective solution willing to make the most of familiar and governments economical constraints willing to alleviate the most urgent impact of the most vulnerable energy poor families.

### **Principal aims and objectives**

The aim of this paper is to present the methodology, observations and findings resulting from a case study of a low cost thermal refuge intervention for a family in extreme poverty in Pamplona (North of Spain). This case study is part of the results of the pilot project “Against energy poverty: monitor, educate and protect” carried out in collaboration with Cáritas Social Services and the University of Navarra Tantaka’s Charity Group with the aim of defining alternative low cost protecting solutions for the most vulnerable energy poor cases in our context.

The main goal of this intervention was to improve the thermal conditions and comfort of this family declaring being unable to maintain comfortable conditions at home. For this purpose, four main objectives were defined to assess the suitability of the solutions adopted:

- To evaluate the problem. Assess the main causes and effects of the inability of this family to reach adequate comfort conditions at home.
- Assess possible solutions and means that could be applied at a very low cost.
- To implement these solutions
- Validate the suitability of the solutions adopted. Assess the effects on comfort, cost, viability.

### **Methodology**

A specific methodology following the above mention aims was developed to assess the progress of this project. For the evaluation of the problem, three main tasks were carried out: a personal interview, concerning household characteristics and home behavior; an inspection of the dwelling and systems for the definition of its thermal and energy performance; and the installation of temperature, humidity and CO<sub>2</sub> sensors for the evaluation of the real environmental indoor indices, heating and ventilation patterns. Measurements took place from December 2014 to February 2015.

Secondly, after analyzing the previous data, energy simulation of possible intervention solutions was carried out and the decision on final solutions was weighted according to the findings, necessities of the family and the technical and economical constraints we were assuming. Thereafter, the different strategies were applied in different phases during the year 2015 in collaboration with volunteers and the family itself that was involved in all the process of decision making and development. Finally, for the validation of the efficacy of the intervention personal follow up visits and interview were carried out as well as a final monitoring phase for the evaluation of the effect of the measures on thermal performance of the dwelling.

## Assessing the problem: Building, familiar and thermal characterization.

High familiar vulnerability. The family studied was formed by a young couple with a newborn baby. At the moment of the intervention the family was receiving social subsidies, a total amount of 650 Euros per month that were mainly used for paying the rent of the house, 400 Euros per month. Also due to a low level of education the family members were unable to access to any stable job during a long period of time. Not only the family was living below the threshold of severe poverty but also was experiencing a high level of social exclusion.

Low energy efficient dwelling and systems. Added to this, this family inhabited a poor energy efficiency dwelling from the 70s, in a medium-low income neighborhood, without insulation, moderate air infiltrations, without centralized heating system and a precarious butane boiler for domestic hot water. A punctual butane stove and an electric radiator were used for heating. The total amount of energy expenses accounted an amount of 11,4% without reaching comfortable conditions.

Vulnerable building context. In addition to the low energy efficiency of the home, we can see in this infrared image (Figure1, left) the added negative effect that a vulnerable context have on the thermal performance of the dwelling. Interior walls, floors and ceilings at this context become also an important way of energy leakage in the home.

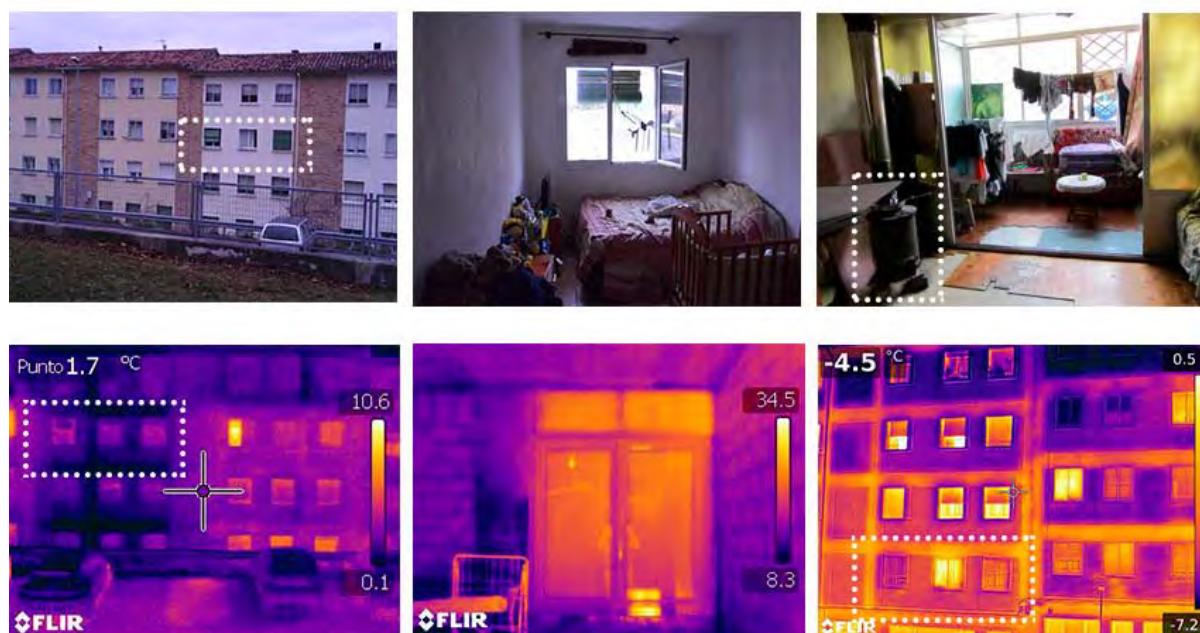


Figure1. Up (left) intervention house (central) intervention bedroom (right) parents house, chimney.  
Down (left) Infrared image of intervention house and unoccupied bedroom (central) and parents house (right)

Inadequate indoor environmental conditions. The temperature patterns from the couple's house are characterized by irregular pulses of one to two hours of heating, mainly in the living room and bedroom at night. The thermal variation in the house reached up to 10 °C between different rooms during heating periods. The average temperature in the living room was 16.5 °C and 14.4 °C in the master bedroom. 12 °C in the rest of the house. As declared by the family a minimum level of comfort is achieved by direct radiation from the heating stove and radiator (personal comfort) and thanks to a higher level of clothing.

However this low intensity heating hinder the increase of surfaces temperatures, walls, ceilings and floors (12°C) enhancing a greater feeling of discomfort and forcing a faster dropping down of air temperatures when heating systems are switched off.

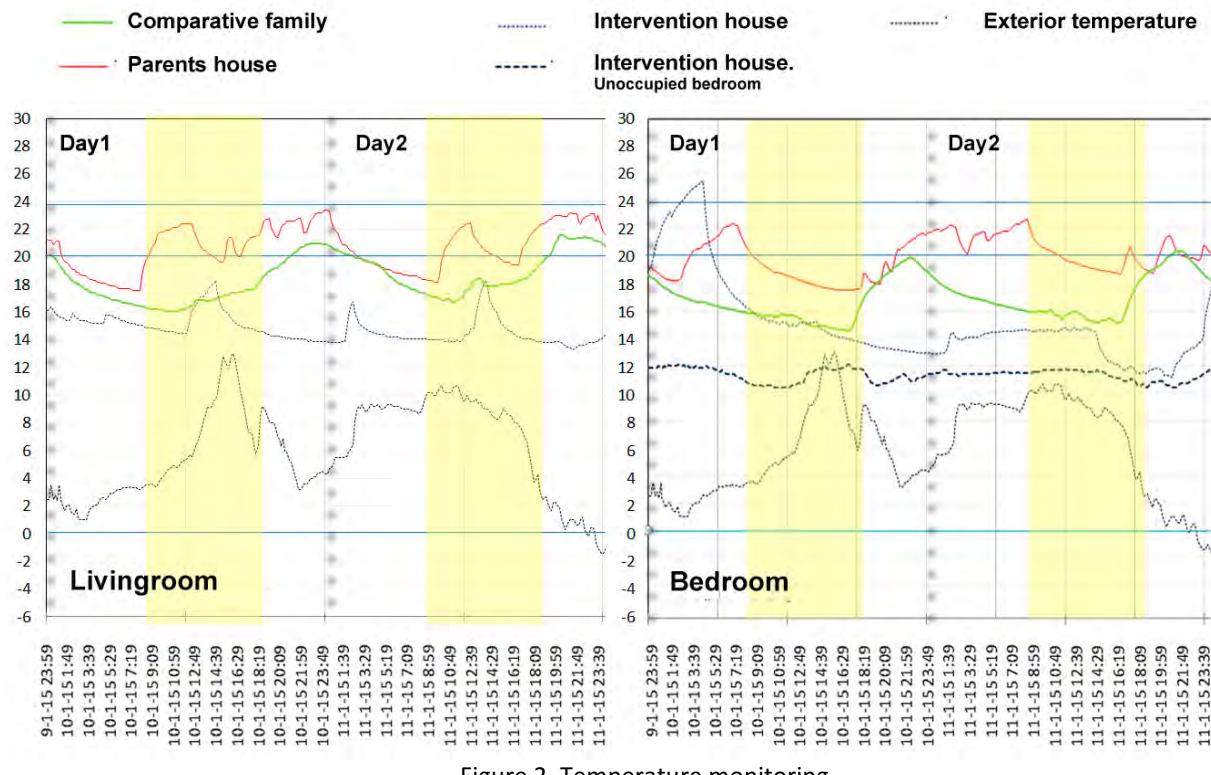


Figure 2. Temperature monitoring

Also, ventilation patterns were detected to be excessive throughout the day, mainly because of the need of ventilation due to high levels of humidity and CO<sub>2</sub> levels measured as a consequence of the combustion means of heating but also due to other bad habits – drying of clothes, pets and smoke-. Damp and mould formation on the contrary was less likely to appear due to this high rate of ventilation and condensation formation appeared only in windows after night periods.

Oftenly and mainly during colder periods of time, the family tended to move to their parents house to stay warmer, whose situation, also of a great vulnerability passed through a fundamental difference, a fireplace of wood, precariously installed in the cooker hood. A great relief but also a burden for the familiar dependency and security due to this sort of inadequate means of heating that a lack of resources force some families to use.

From the monitoring of temperatures we can observe both vulnerable dwellings, the couples house (in blue) and the parents house (in red). As a reference we present the contrast with a working middle class dwelling monitored at the same time representing a more stable temperature pattern (in green), all of them of the same construction and typological type.

### Intervention strategies

Two main sets of strategies were defined to improve the thermal conditions and comfort perception of the dwelling, on the one hand, reducing as possible the energy losses of the dwelling and reducing the impact of cold surfaces on operative temperature, and in the

other hand, improving control, knowledge and habits of the householders in order to improve their adaptive thermal strategies and resulting perception of comfort at lower temperatures. Also two main limitations influenced the decision making, costs, due to a limited budget of 1200 Euros, and technical possibilities, only interior fabric could be modified without harming considerably interior surfaces, as it was agreed with the landlord of the flat.

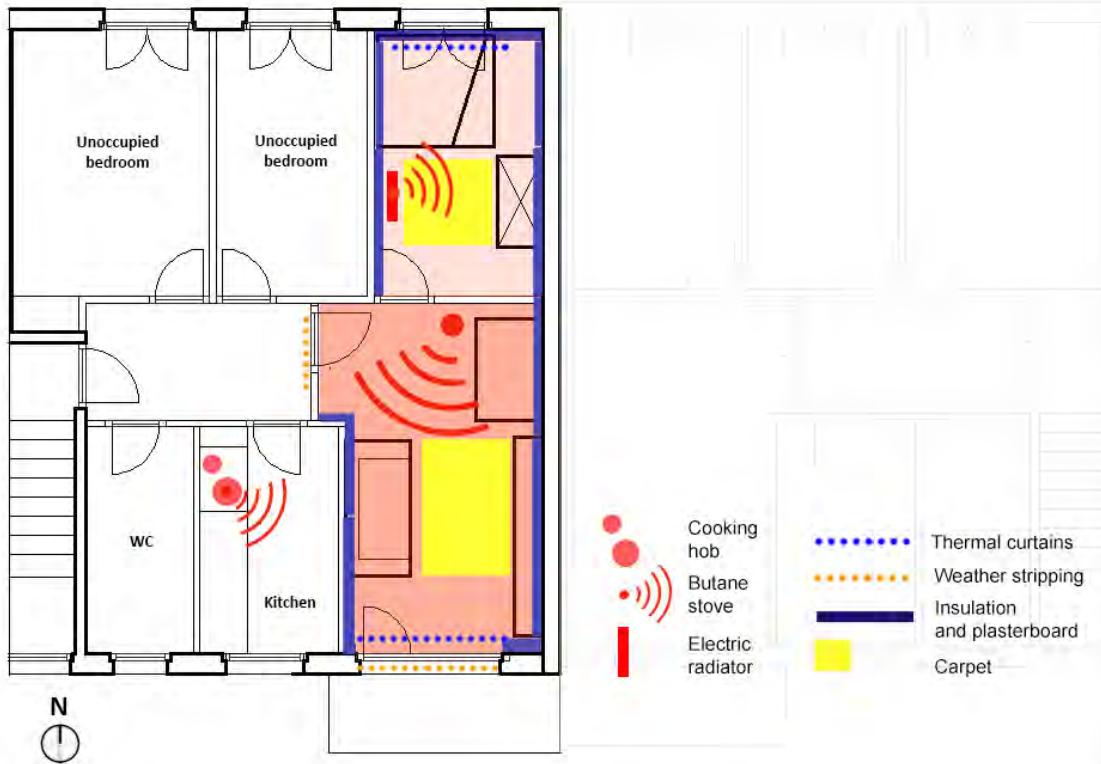


Figure 3. Floor plan and intervention measures

The first set of strategies centered on the thermal sectorization and adaptation of main living spaces of the dwelling, living room and master bedroom, creating a more protected and cozy space, a sort of thermal refugee within the dwelling, easier to heat where householders could stay comfortably with the same heating means they had available, as any other heating system was possible to implement due to the cost.

To this end mineral wool inner insulation (5cm) and plasterboard were added in both exterior and interior walls based on the following reasons. Firstly, due to the high differences of temperatures between interior spaces (non heated rooms, non heated neighbors), also for the reduction of the effect of cold walls on comfort and the impact of thermal inertia in a house irregularly occupied that needed to be quickly warmed up. Insulation in ceilings and floors of these bedrooms was also considered but finally not implemented. Big carpets were bought instead to insulate from the terrazzo tiled floor. Also thermal curtains were developed and installed due to the lack of rolling shutters in the bedrooms and weather stripping in windows and interior doors were used to reduce the effect of air infiltrations. Special effort was done also in modifying the thermal perception of these spaces, changing the wall's colors, lights, and the re-arrangement of furniture in the space.

As a second set of actions, giving control and information to the householders was fundamental considering that their inability to adapt themselves to their lack of resources was determined partly by a lack of information and proper habits and due to a high level of social exclusion.

Concerning control, thermometers were given to facilitate an adequate knowledge of the temperature levels reached with the butane stove and electric radiator allowing them to maintain an adequate temperature level, not too high, in order to save up, nor to low, reducing the exposure to low temperatures of the most vulnerable member of the family, the baby. Also, in order to maintain a minimum level of temperature at night, and in order to preheat the dwelling at a certain hours, before arriving home, time controlled electric plugs were provided. In addition, estimations about the energy costs of different heating patterns, combining butane and electricity were given to improve familiar expenses planification. To these set of actions, also other information tips were given about home behavior and energy conservation - ventilation patterns, thermal curtains use, etc.



Figure 4. Intervention measures

## Results

Overall the set of strategies applied in this pilot project were positive improving the indoor environmental conditions as well as the comfort vote of the householders. Three main effects are worth mentioning as a critical revision of the strategies adopted in this intervention.

Improve of average indoor temperature. As can be seeing in the figure 5, in which we performed a monitoring comparative, heating at the same time two bedrooms, the one insulated and the other one next to it not insulated, with the same surface, and taking into account the limitations this sort of comparative have, we could detect an average improve between 1,5°C -2°C in average indoor and wall surface temperature with a similar heating pattern. Another effect that can be seen is the reduction of heating time to achieve similar indoor temperatures that considering the means of heating available, a butane stove, reduces CO<sub>2</sub> and humidity concentrations. In this sense, opening slightly windows meanwhile the butane stove was on reduced considerably the negative effect of CO<sub>2</sub> and humidity concentrations but assuming a negative effect on comfort due to air currents and

on higher heating time to achieve the same indoor temperatures. As a negative revision, the temperature dropping was higher than expected and ceiling insulation should have been done as well as higher insulation levels.

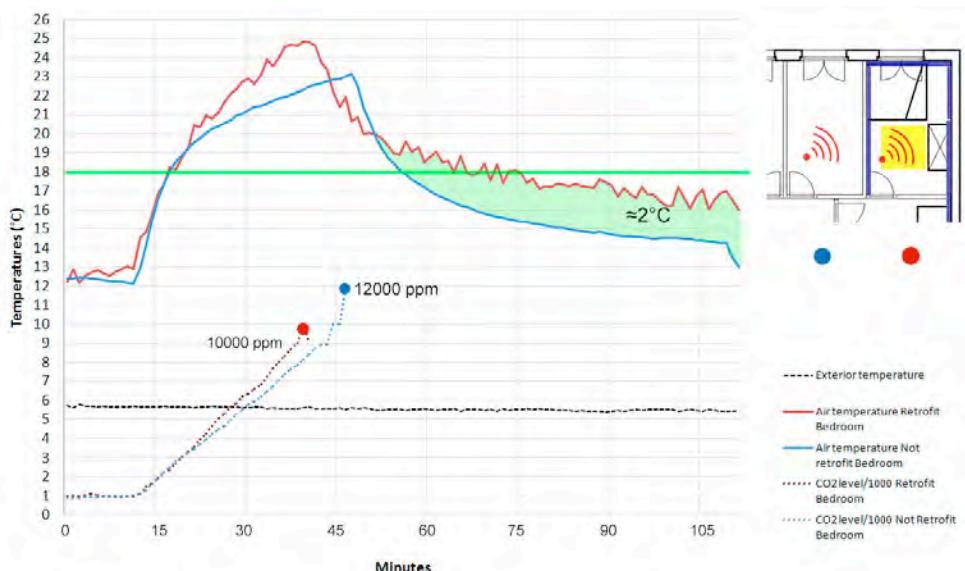


Figure 5.Temperature comparative between retrofitted and not retrofitted bedroom

Increase in the comfort perception. Most remarkable aspect in this intervention was the improvement of the comfort vote of the householders, declaring a notable and positive change in the comfort perception and feeling. The combined positive impact of increased air and surface temperature, the reduction of infiltrations and the improved control that a thermometer provided to them, as well as the effect of preheating at certain hours thanks to the time controlled electric plugs, improved their acceptance to a flat in which they were unable to stay comfortably.



Figure 6. Infrared image of intervention measures

Estimation of possible savings. Considering the savings that this intervention may produce, it fundamentally depends on the behavioral changes and it has not been controlled afterwards. As estimated with the simulation calculations, with a similar heating pattern, the effect on savings would be subtle, accounting an amount of 70 Euros annually. Taking into account that previous heating patterns were considerably insufficient due to economical constraints and lack of control on the familiar expenses due to the mentioned low level of planification and education, energy expenses may remain similar or higher to reach appropriate levels of comfort.

## **Conclusions**

The provision of proper indoor environmental conditions is a requirement for comfort, health and wellbeing for human beings. A need that an important number of families can't afford or maintain nowadays in our modern society. High-performance building services and deep energy retrofits are considered nowadays the most suitable solution for the improvement of energy efficiency and the reduction of CO<sub>2</sub> emissions, and ultimately for the provision of adequate and affordable comfort.

Nevertheless, government and familiar economical constraints nowadays challenge the development of these solutions in the extensive and inefficient building stock characteristic of our contexts. In particular are the most economically deprived the most in need of such solutions and oftenly the most impeded to access to them.

Therefore, alternative ways of intervening in the efficacy of these vulnerable families in providing comfort are required. Complementary solutions to economical incentives, winter or cold payments, better quality and access to social housing, or other political measures, that could in a temporary way provide an effective way of assuring comfort at an affordable cost. Solutions that implied not only less cost, and less barriers, but fundamentally a greater impact in comfort. Solutions from the cheapest, as behavioral education, control or tariffs information, to other low cost micro-retrofitting interior solutions, like thermal refuges that could provide spaces of comfort in the face of constraints and climatic hazards (Roaf et al, 2009) that could be in addition applied in a shorter term and in larger scale by individuals, replacing yearly lost palliative subsidies.

## **Acknowledgments**

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## **References**

- Bouzarovski–Buzar, S. (2011). Energy poverty in the EU: a review of the evidence. In DG Regio Workshop on Cohesion Policy Investing in Energy Efficiency in Buildings. Brussels.
- Kolokotsa, D., & Santamouris, M. (2015). Review of the indoor environmental quality and energy consumption studies for low income households in Europe. *Science of the Total Environment*, 536.
- Papada, L., & Kaliampakos, D. (2016). Measuring energy poverty in Greece. *EnergyPolicy*, 94, 157-165.
- Roaf, S., Crichton, D., & Nicol, F. (2009). Adapting buildings and cities for climate change: a 21st century survival guide. Routledge.
- Ugarte, S., van der REE, B., VOOGT, M., EICHHAMMER, W., ORDOÑEZ, J. A., REUTER, M., & Villafafila Robles, R. (2016). Energy efficiency for low-income households.
- Santamouris, M., Alevizos, S. M., Aslanoglou, L., Mantzios, D., Milonas, P., Sarelli, I., ... & Paravantis, J. A. (2014). Freezing the poor—Indoor environmental quality in low and very low income households during the winter period in Athens. *Energy and Buildings*, 70, 61-70.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Assessing the impact of zoning on the thermal comfort analysis of a naturally ventilated house during early design considering closed internal doors

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**Abstract:** Thermal performance computational simulation is getting more important every time. However, it requires a lot of time, specialized technicians, high budgets and a very detailed project. Currently, there are simplified tools but they do not offer accurate results like other more complex methods. Due to that, this paper proposes a simplification of the simulation method, without compromising its results. This simplification would help architects and engineers to verify the buildings thermal comfort in the early stages of design. The simplification suggested for this paper is related to thermal zoning in the computational simulation program EnergyPlus. The studied building is a naturally ventilated social house of approximately 51m<sup>2</sup>. This house is located in three cities of Brazil (Curitiba, Manaus and São Paulo), corresponding to different climates. It has four rooms (bedroom 1, bedroom 2, living room – kitchen and bathroom). This house is modeled in EnergyPlus in two ways: like a multi zone model (MZM) and like a single zone model (SZM), that is, the entire floorplan considered just like one zone. This paper evaluates the accuracy between the results of both modeling options and it studies the influence of thermal zone modeling considering various schedules for internal doors opening and closing.

**Keywords:** Thermal comfort, computational simulation, modeling simplification, natural ventilation.

### Introduction

Building performance simulation tools are commonly used in the final stages of the project, when most decisions have already been made. Nonetheless, it is in the early design stages when designers demand quick building performance feedback for evaluating different design alternatives (Al Gharably et al., 2015; Hensen et al., 2004; Hygh et al., 2012; Struck and Hensen, 2007).

Building performance simulation tools are complex. Their use requires substantial time by technicians, a specialized team with a vast multidisciplinary knowledge, considerable budgets and a detailed project in the early stage of design (Catalina et al., 2008; Signor et al., 2001). To help address these challenges, this paper describes a simplification of the simulation method by examining ways to reduce the number of thermal zones, without compromising its results and reducing the simulation time. The aim of this work is to simplify building modeling in EnergyPlus (EERE, 2013a), one of the most commonly used programs for building thermal performance analysis.

For HVAC systems, EnergyPlus manual recommends creating one thermal zone for each room with different set point temperatures. However, it does not include any

recommendation for modeling the thermal zones for naturally ventilated houses (EERE, 2013b). In this context, Silva and Ghisi (2014) simplified the thermal zones of a three-story public building with an HVAC system in EnergyPlus by removing the internal walls and combining the thermal zones, ensuring to create an equal thermal mass with the same surface and thermal capacity of the internal walls. This approach achieved sufficient accuracy. Favretto et al. (2015) carried out a comparison, using EnergyPlus, between single zone models (SZMs) and multi zone models (MZMs) for a naturally ventilated four-room one-storey social house of approximately  $51\text{m}^2$ . The SZM represented the entire floorplan as one zone with adjustments in the thermal mass and capacity. The results showed low differences between the thermal comfort predictions estimated using the SZM and MZM representations.

The work presented in this paper complements the work reported by Favretto et al. (2015), in which they assumed that the internal doors were open. According to an interview done at different cities that represent diverse climates in Brazil, only half of the families usually keep the internal doors open during the whole day, and the other half closes them in the night (Casatejada and Chvatal, 2017); closing the doors can influence in the thermal zones simplifications in naturally ventilated houses. We extend Favretto et al.'s study by investigating the effect of different opening/closing schedules for the internal doors on thermal comfort predictions using a SZM representation.

## Methodology

### **General features**

The building studied in this work, which is same as the one reported in Favretto et al. (2015), was simulated in the EnergyPlus program (EERE, 2013a). This is a naturally ventilated one-story isolated social house of approximately  $51\text{ m}^2$  (Figure 1) composed of a living room - kitchen (LVRK), two bedrooms (BDR\_1 and BDR\_2), a bathroom and a gable roof with a non-ventilated attic. For purposes of modeling simplification, two models were considered: a Multi Zone Model (MZM) and a Single Zone Model (SZM). The MZM considers each room as a thermal zone, while in the SZM, the entire floor plan is considered as a single thermal zone. In both cases, the attic is considered as an independent thermal zone. In SZM, a thermal mass equivalent to the eliminated internal partitions was included.

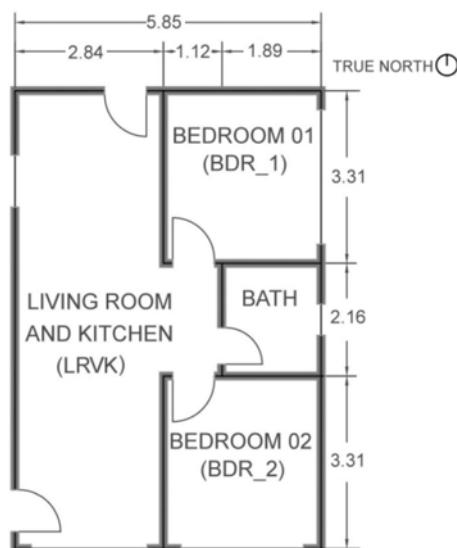


Figure 1. Floor plan of the base model (orientation north 0°). Source: Adapted from Favretto et al. (2015)

The following cities were studied: Curitiba, Manaus and São Paulo, corresponding to colder, warmer and mild climates, respectively; Favretto et al. (2015) also reported results for these cities. In all three cities, the main direction of the wind is eastward or southeastward. Accordingly, three solar orientations to be studied were defined: base model ( $N0^\circ$ ), worst ( $N90^\circ$ ), and best ( $N270^\circ$ ); the best and worst orientations were selected to most favor and least favor, respectively, natural ventilation.

### **Cases considered**

Three cases with different conditions for internal doors, namely, always open, always closed, and open on a schedule (closed at night, from 10 pm to 7 am), were analyzed to verify the influence of the internal door condition on the thermal zones simplification in the SZM approach. External doors were assumed to be always kept closed.

### **Simulations settings**

In all cases, the human occupancy and the internal gains produced by lights and electric equipment were modeled based on the values suggested by the Brazilian thermal regulations (INMETRO, 2012), and the house construction properties were same as those used in the study by Favretto et al. (2015), which are summarized in Table 1.

Table 1. Summary of construction properties used in all cases. Source: Favretto et al. (2015)

Wall properties	$U=2.46 \text{ W}/(\text{m}^2\cdot\text{K})$	$HC=150\text{KJ}/(\text{m}^2\cdot\text{K})$	$\alpha=0.4$	Notations: $U$ = U-value $HC$ = Heat capacity $\alpha$ = Solar absorptance
Roof properties	$U=1.8 \text{ W}/(\text{m}^2\cdot\text{K})$	$HC=185\text{KJ}/(\text{m}^2\cdot\text{K})$	$\alpha=0.7$	
WWR	40% (Window-to-Wall Ratio); 50% (Rest of the rooms windows effective area); 100% (Bathroom window effective area)			

The natural ventilation was modeled using the AirflowNetwork, the natural ventilation module in EnergyPlus. In this module, the window opening is assumed to be controlled by temperature; the set point temperature used was the comfort temperature calculated by the Adaptive Comfort Index ASHRAE-55 (ASHRAE, 2013). Thus, natural ventilation occurred only when the following conditions were met simultaneously:

- Zone temperature > Outdoor temperature
- Zone temperature > Set point temperature
- Natural ventilation is allowed only between 7 am and 10 pm.

### **Outputs**

The EnergyPlus simulation outputs analyzed included: a) Zone Mean Air Temperature and b) Zone Operative Temperature. Since the occurrence of natural ventilation depends on the hourly value of the air temperature, it is important to know the mean air temperature. The operative temperature, which is the arithmetic mean of the air temperature and the average radiant temperature, is used to calculate the discomfort degree-hours according to the Adaptive Comfort Index ASHRAE-55 (ASHRAE, 2013). This method analyzes the thermal comfort of occupants in naturally ventilated buildings assuming that people tend to adapt to the conditions of their outside environment. Thus, the comfort temperature was calculated for an acceptability range of 80% of the people satisfied with the temperature.

## Results and analyses

The difference ( $\Delta = \text{SZM} - \text{MZM}_{\text{room}}$ ) in the simulated hourly values obtained for the zone temperature using the SZM approach and temperature in each long-stay room using the MZM approach is used to assess the validity of using the SZM-based simplified approach. The MZMs are modeled in three different ways: internal doors always open, always closed and on a schedule (closed at night). If the difference  $\Delta$  is positive (or negative), then it means that there is a temperature overestimation (or underestimation) by the SZMs compared to those by the MZMs.

### Air temperature and Operative temperature

In this section, comparisons of the air and operative temperatures predicted by SZMs and MZMs are carried out.

Equation 1 represents an annual aggregate measure of temperature difference based on the hourly room temperature estimated by the two different methods; in the SZM approach where there are no room partitions, all rooms are assumed to be at the single zone temperature in each hour. This equation was applied for air temperature and operative temperature values.

$$\Delta T^{\text{room}} = \frac{\sum_{i=1}^{8760} (T_i^{\text{SZM}} - T_i^{\text{MZM,room}})}{365*24} \quad (1)$$

where:

$\Delta T^{\text{room}}$ : Annual average difference between  $T_i^{\text{SZM}}$  and  $T_i^{\text{MZM,room}}$  ( $^{\circ}\text{C}$ ).

$T_i^{\text{SZM}}$ : SZM hourly air temperature or operative temperature ( $^{\circ}\text{C}$ ).

$T_i^{\text{MZM,room}}$ : MZM hourly air temperature or operative temperature for each long-stay room ( $^{\circ}\text{C}$ ).

The results obtained from this equation for both the air and operative temperatures were similar to each other; thus, only the results for the air temperature are shown in the Figure 2. Overall, the differences ( $\Delta T^{\text{room}}$ ) between the SZM-based and MZM-based temperature values are consistently highest for the always-closed-internal-door cases, followed by the doors-closed-on-a-schedule cases, and then the doors-always-open cases. In all cases, the negative differences are mostly greater than the positive ones, implying a systematic underestimation by the SZMs. Smaller average differences are observed in all three orientations for Manaus (warmer climate) than for Curitiba (colder climate) and São Paulo (mild climate).

In Curitiba, the [minimum, maximum] values of the hourly average differences between SZMs and MZMs in the three orientations are: [-0.38 $^{\circ}\text{C}$ , 0.34 $^{\circ}\text{C}$ ] (open doors); [-0.59 $^{\circ}\text{C}$ , 0.47 $^{\circ}\text{C}$ ] (doors on a schedule); and [-0.68 $^{\circ}\text{C}$ , 0.51 $^{\circ}\text{C}$ ] (closed doors). In Manaus, differences are: [-0.24 $^{\circ}\text{C}$ , 0.26 $^{\circ}\text{C}$ ] (open doors); [-0.35 $^{\circ}\text{C}$ , 0.26 $^{\circ}\text{C}$ ] (doors on a schedule); and [-0.45 $^{\circ}\text{C}$ , 0.28 $^{\circ}\text{C}$ ] (closed doors). In São Paulo, the differences are: [-0.39 $^{\circ}\text{C}$ , 0.32 $^{\circ}\text{C}$ ] (open doors); [-0.57 $^{\circ}\text{C}$ , 0.43 $^{\circ}\text{C}$ ] (doors on a schedule); and [-0.61 $^{\circ}\text{C}$ , 0.48 $^{\circ}\text{C}$ ] (closed doors).

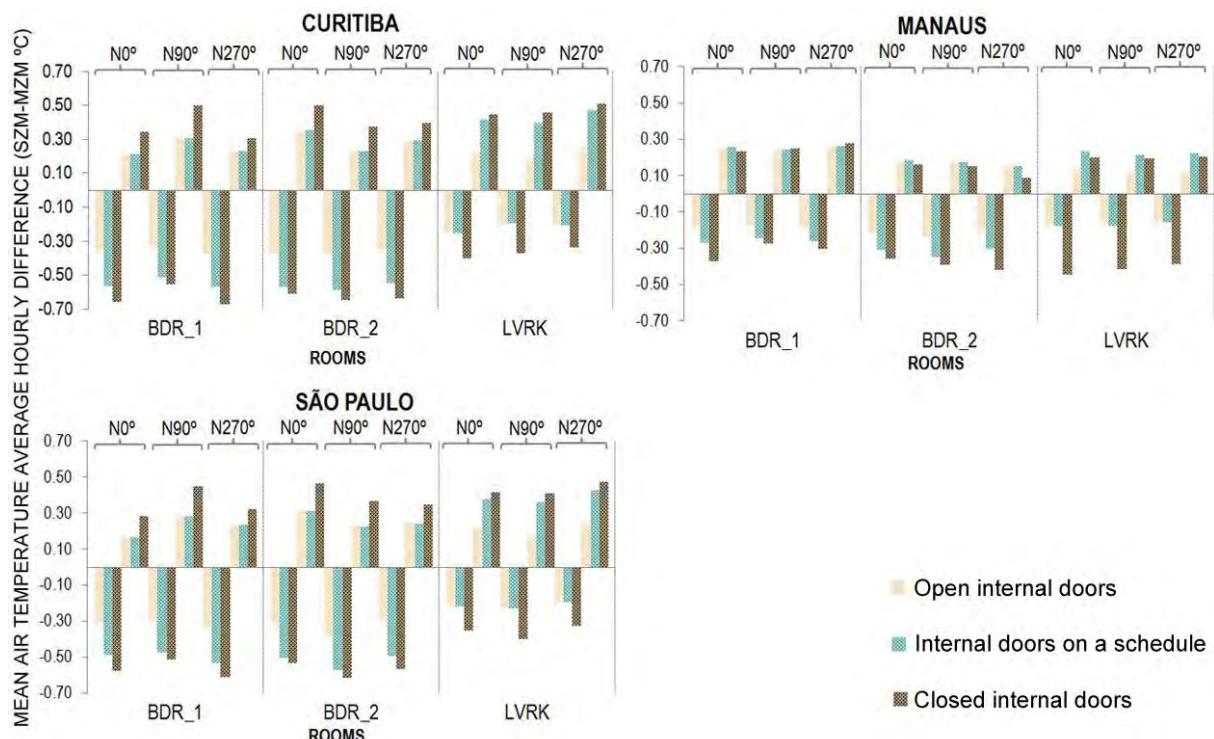


Figure 2. Annual average hourly air temperature difference between SZMs and each long-stay room of MZMs for three internal door schedules; averages are calculated separately for the positive and negative  $\Delta T^{room}$  values ( $^{\circ}\text{C}$ ).

Figure 3 shows the frequency of occurrence of discrete interval values of absolute difference in hourly air temperature between SZM and MZM estimates. As all orientations resulted in similar trends, only the results for N0° orientation are shown. In Curitiba, the differences in the estimated temperatures are lower than 0.2°C for 36.2% (open doors), 29.1% (doors on a schedule) and 20.9% (closed doors) of the hours in a year. In Manaus, the differences are lower than 0.2°C for 63.9% (open doors), 45.1% (doors on a schedule) and 33.5% (closed doors) of the hours in a year. In São Paulo, the differences are lower than 0.2°C for 40.6% (open doors), 32.1% (doors on a schedule) and 24.2% (closed doors) of the hours in a year. These percentages are based on the average of the three long-stay rooms (BDR\_1, BDR\_2 and LVRK). Curitiba and São Paulo have the majority of the hours of the year with a difference between 0 to 0.4 °C. However, for Manaus, the differences are even lower, with most of hours of the year in the  $\leq 0.2^{\circ}\text{C}$  range for all three internal door schedules.

Table 2 shows the minimum and maximum annual differences of the air temperature (in a specific day and hour) between SZM-based and MZM-based estimates. The largest values found (for each internal door schedule) are: -1.94°C in BDR\_2 for Manaus/N270° (open doors); -1.92°C in LVRK for São Paulo/N270° (doors on a schedule); and -2.31°C in LVRK for Manaus/N90° (closed doors).

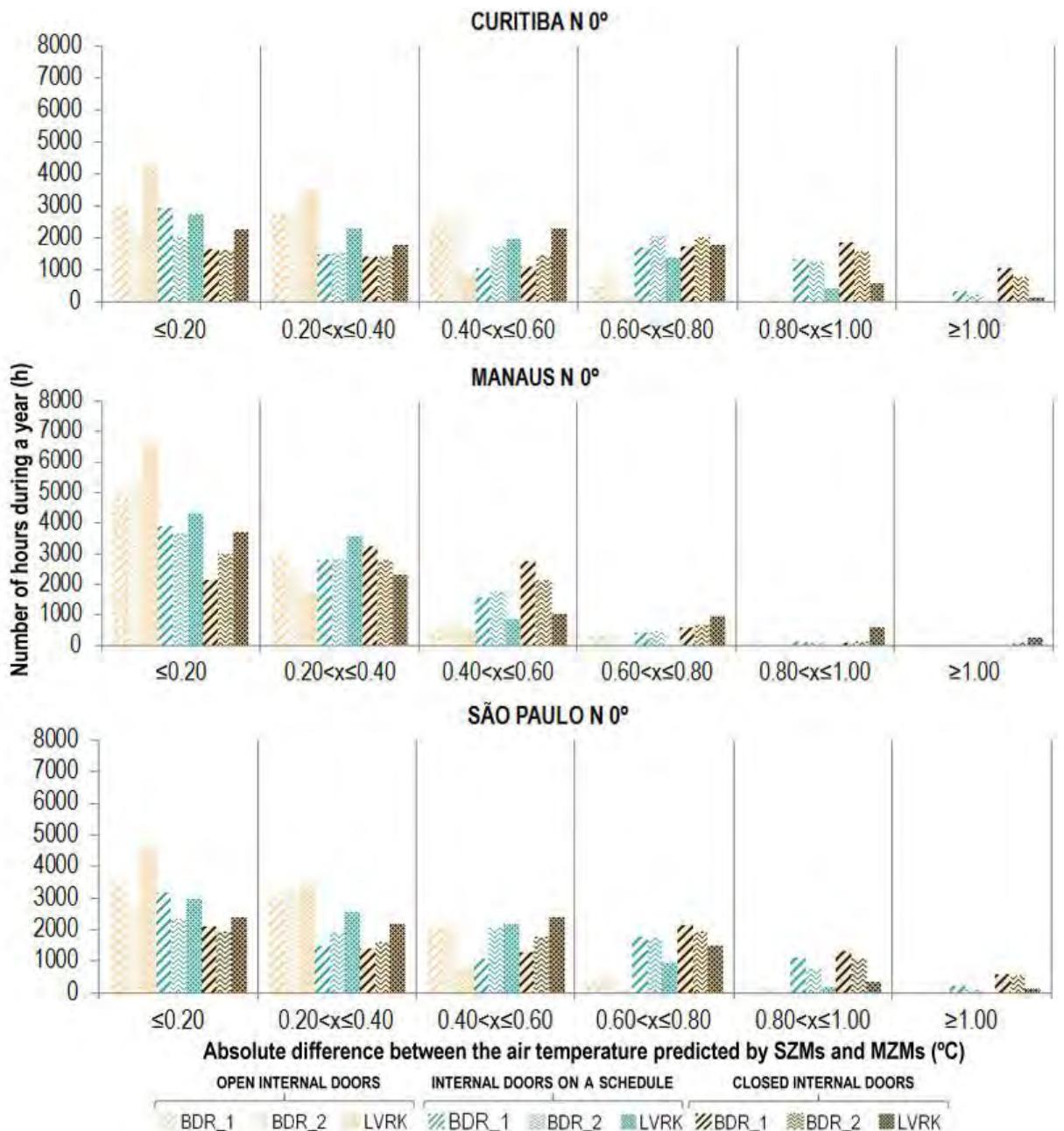


Figure 3. Distribution of hourly absolute differences between the air temperature predicted by SZMs and MZMs over a year.

Table 2. Maximum and minimum annual differences of air temperature between SZM-based and MZM-based estimates.

N 0°						N 90°						N 270°														
OPEN		ON A SCHEDULE		CLOSED		OPEN		ON A SCHEDULE		CLOSED		OPEN		ON A SCHEDULE		CLOSED										
CURITIBA																										
1.12	1.16	0.79	1.12	1.17	1.06	1.47	1.65	1.32	1.27	1.01	0.69	1.27	1.00	0.96	1.67	1.47	1.08	0.98	1.14	0.85	0.97	1.18	1.27	1.44	1.38	1.24
-1.24	-1.55	-1.36	-1.44	-1.89	-1.27	-2.09	-1.87	-1.93	-1.00	-1.36	-1.51	-1.25	-1.71	-1.44	-1.46	-1.74	-1.72	-1.32	-1.29	-1.51	-1.69	-1.51	-1.45	-1.83	-1.87	-1.65
MANAUS																										
1.51	0.68	0.65	1.51	0.68	0.67	0.86	0.76	0.96	1.30	0.71	0.81	1.30	0.70	0.82	0.77	0.77	0.76	1.56	0.67	0.67	1.56	0.67	0.68	1.11	0.72	0.72
-0.78	-1.56	-0.92	-0.96	-1.56	-0.92	-1.53	-1.97	-1.65	-0.83	-1.33	-0.93	-1.33	-0.93	-1.48	-2.02	-2.31	-0.81	-1.94	-1.21	-0.91	-1.93	-1.21	-1.25	-1.86	-2.00	
SÃO PAULO																										
1.00	1.06	0.78	0.99	1.03	0.97	1.44	1.66	1.31	1.12	0.87	0.71	1.12	0.74	0.86	1.69	1.35	0.95	1.02	0.90	0.93	1.01	0.85	1.13	1.25	1.34	1.14
-1.43	-1.59	-1.53	-1.38	-1.58	-1.45	-1.97	-1.74	-2.02	-1.17	-1.81	-1.35	-1.30	-1.38	-1.40	-2.07	-1.99	-1.79	-1.63	-1.83	-1.77	-1.63	-1.92	-1.88	-2.11	-1.90	
BDR_1      BDR_2      LVRK																										

### Discomfort degree-hours

The annual average hourly discomfort degree-hours difference ( $\Delta D^{room}$ ) between SZM-based and MZM-based temperature estimates in each long-stay rooms for one year are calculated using Equation 2. This is calculated separately for heat and cold discomfort.

$$\Delta D^{room} = \frac{\sum_{i=1}^{8760} (D_i^{SZM} - D_i^{MZM})}{365*24} \quad (2)$$

where:

$\Delta D^{room}$ : Annual average difference between  $D_i^{SZM}$  e  $D_i^{MZM}$  ( $^{\circ}\text{Ch}$ ).

$D_i^{SZM}$ : SZM hourly discomfort degree-hours by heat or by cold ( $^{\circ}\text{Ch}$ ).

$D_i^{MZM}$ : MZM hourly discomfort degree-hours by heat or by cold for each long-stay room ( $^{\circ}\text{Ch}$ ).

Figure 4 shows the annual average difference of discomfort degree-hours by heat and by cold, respectively, between SZM-based and MZM-based temperature estimates; results in this figure include all cities, orientations and the three internal-door schedules. It is observed that the smaller values of discomfort by cold occur in Manaus (warmer climate), while the minimum discomfort by heat occurs in Curitiba (colder climate) and São Paulo (mild climate). The highest differences are associated with the closed-door cases, followed by the doors-on-a-schedule cases, and then the always-open cases.

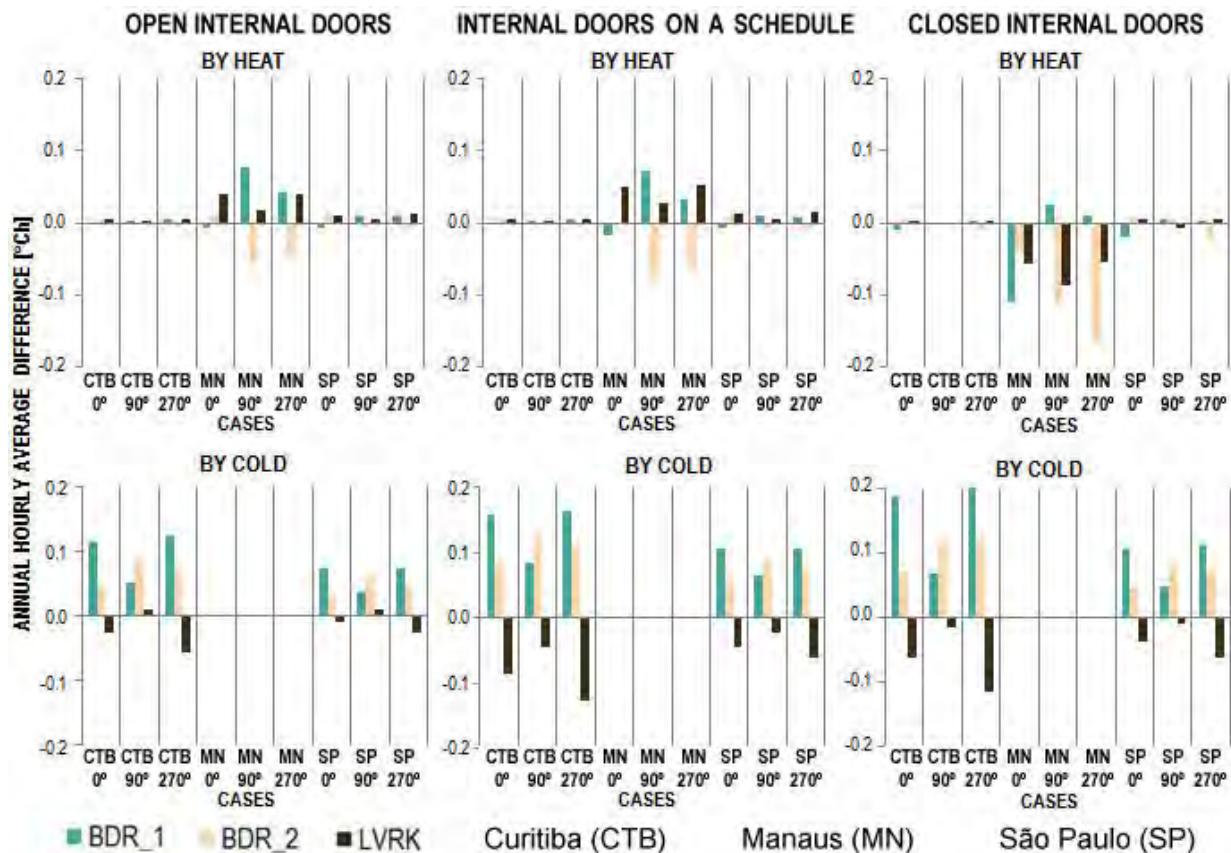


Figure 4. Annual average difference between SZM-based and MZM-based temperature estimates in hourly discomfort by heat and cold.

In the simulations for the open-door cases, the maximum average difference of discomfort degree-hours by heat is +0.077 in the BDR\_1 for Manaus/N90°, and by cold is +0.122 in the same room for Curitiba/N270°. In the cases with internal doors on a schedule,

the highest difference of discomfort by heat is -0.079 in BDR\_2 for Manaus/N90°, and +0.164 by cold in BDR\_1 for Curitiba/N270°. Finally, in the simulation with the closed internal doors, the highest difference of discomfort by heat is -0.164 in BDR\_2 for Manaus/N270°, and +0.208 by cold in BDR\_1 for Curitiba/N270°.

## Observations and Final Remarks

This paper described and analyzed a modeling simplification approach based on thermal zone representation, i.e., Single Zone Models (SZMs) versus Multi Zone Models (MZMs), for a naturally ventilated building. Three internal door schedules were considered: always open, open on a schedule (closed at night) and always closed, to evaluate the impact of the proposed SZM-based simplification approach compared to the MZM approach on the zone temperature as well as hourly discomfort predictions. Also, three Brazilian climates were studied: Curitiba (colder climate), Manaus (warmer climate) and São Paulo (mild climate). The main conclusions are the following: a) in general, SZMs compared to MZMs underestimate temperature values for all cases; b) smaller differences in SZM vs. MZM predictions occur for cases in Manaus; and c) SZM vs. MZM predictions for cases with always-open internal doors are most similar in all three cities and orientations, although, differences found for models with always-closed doors are significantly lower. In follow up work, other floorplans, geometry proportions, and other parameters like window opening schedule and sizes and construction materials should be investigated.

## References

- Al Gharably, M., DeCarolis, J. F. and Ranjithan, S. R. (2015). An enhanced linear regression-based building energy model (LRBEM+) for early design. *Journal of Building Performance Simulation*, (2012), 1–19.
- ASHRAE. ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. (2013). Atlanta.
- Casatejada, M. P. and Chvatal, K. M. S. (2017). Comparison between the usual and recommended opening schedules for both windows and internal doors in Brazilian houses. *Internal Report*, 1–10.
- Catalina, T., Virgone, J. and Blanco, E. (2008). Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy and Buildings*, 40(10), 1825–1832.
- EERE. (2013a). EnergyPlus v8.1. US: Department of Energy Efficiency and Renewable Energy, Office of Building Technologies.
- EERE. (2013b). Getting Started. US: Department of Energy Efficiency and Renewable Energy, Office of Building Technologies.
- Favretto, A. P. O., Rossi, M. M., Anchieto, C. and Chvtal, K. M. S. (2015). Assessing the impact of zoning on the thermal comfort analysis of a naturally ventilated house during early design. In *14th International Conference of the International Building Performance Simulation Association*. (p. 8). Hyderabad.
- Hensen, J., Djunaedy, E., Radošević, M. and Yahiaoui, A. (2004). Building performance simulation for better design : some issues and solutions, (2015), 19–22.
- Hygh, J. S., DeCarolis, J. F., Hill, D. B. and Ranji Ranjithan, S. (2012). Multivariate regression as an energy assessment tool in early building design. *Building and Environment*, 57, 165–175.
- INMETRO - INSTITUTO NACIONAL DE METROLOGIA, N. E. Q. I. Regulamento técnico da qualidade para o nível de eficiência energética de edificações residenciais (2012). Brazil.
- Signor, R., Westphal, F. S. and Lamberts, R. (2001). Regression analysis of electric energy consumption and architectural variables of conditioned commercial buildings in 14 Brazilian cities. In *Seventh International IBPSA Conference - Building Simulation* (pp. 1373–1380). IBPSA.
- Silva, A. S. and Ghisi, E. (2014). Uncertainty analysis of the computer model in building performance simulation. *Energy and Buildings*, 76, 258–269.
- Struck, C. and Hensen, J. (2007). On supporting design decisions in conceptual design addressing specification uncertainties using performance simulation. In *IBPSA Building Simulation Conference*, 10 (pp. 1434–1439).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Field Study of Thermal Comfort in University Buildings in Malaysia

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**Abstract:** Malaysia experiences hot and humid climate all year round, causing people to rely on Heating, Ventilation, and Air-Conditioning (HVAC) system for cooling purpose. This is no exception in educational buildings, where indoor thermal condition could affect the occupants' performance in learning and teaching activities. This study aimed to estimate the neutral temperature of university building occupants based on field measurements, then compared the results from survey and predicted mean vote (PMV) method. Thermal comfort field survey was conducted in two university campuses in Malaysia, Universiti Teknologi Malaysia (UTM) and Universiti Teknologi MARA (UiTM), in Malaysia. In 2014, approximately 979 responses were collected from the students during learning sessions in classroom, while additional 1114 responses were obtained the following year from postgraduate researchers and staffs in their working spaces. Using regression analysis on surveyed thermal sensation vote (TSV), the occupants' neutral temperature was found at 27.3 °C, which was higher than predicted result at 24.9 °C. The PMV overestimated the occupants' sensation as temperature increases.

**Keywords:** Thermal comfort, Air conditioning, Hot and humid climate

### Introduction

The tropical climate in Malaysia is a conundrum for maintaining thermal comfort. The year-round hot and humid environment (Kottek *et al.*, 2006) means that occupants are unable to effectively cool down their environments naturally. Therefore, the most obvious solution is to rely on mechanical cooling using Heating, Ventilation, and Air-Conditioning (HVAC) systems, which has become the largest consumer of energy in buildings (Saidur, 2009).

In educational settings such as lecture theatres, providing a comfortable thermal environment is a necessity for conducive learning (Clements-Croome, 2001; Corgnati *et al.*, 2007; Astolfi and Pellerey, 2008). Important design considerations such as day lighting, ventilation, and solar control has been subsumed by simpler artificial systems such as artificial lighting and HVAC, in order to provide a controllable, comfortable environment. However, the use of these systems, especially HVAC, in educational settings have other far reaching implications vis-à-vis energy consumption, policy decisions and occupants' well-being. In relation to these matters, more complete information is needed to form a guideline on HVAC design in educational establishments.

The thermal comfort analysis conducted in this study aims to illuminate the thermal perception of building occupants, as a means of providing information on potential energy savings. In order to provide this information, the following study objectives were set: (1) to investigate neutral temperature of university rooms in Malaysia, including classrooms and working spaces; (2) to compare the results of building occupants' thermal sensation vote (*TSV*) based on questionnaire survey and prediction (*PMV*), as well as percentage of dissatisfied (*PPD*).

## **Methodology**

The data for this study was gathered using field surveys, combining field measurement of indoor thermal environment parameters and questionnaire surveys for building occupants. Two universities participated in this study: Universiti Teknologi MARA (UiTM), Shah Alam campus and Universiti Teknologi Malaysia (UTM), Kuala Lumpur campus. Both are located at the Klang Valley, in the south-west of the Malay Peninsula. The Klang Valley experiences a tropical rainforest climate (*i.e.*, year-round hot and humid weather), with the highest mean outdoor air temperature in March and lowest in January, based on the Köppen world climate classification (Kottek *et al.*, 2006).

## **Investigated buildings**

Surveys in the classrooms were conducted in 2014, then the staff offices and postgraduate working spaces in 2015 (Damiati *et al.*, 2016). Classrooms investigated in this study used HVAC systems for cooling, and are occupied during classes by lecturers and students. In total, six classrooms in the Malaysia Japan International Institute of Technology (MJIIT) in UTM, and 14 from the Faculty of Mechanical Engineering in UiTM were surveyed. The university workspaces investigated were located in four postgraduate laboratories in MJIIT as well as in three administrative office buildings in UiTM. These rooms are detailed in Table 1.

Table 1. Building information and number of sample

Space function	University, Campus	Location	Measurement period	Building block	Room code	n
Classroom	UTM, Kuala Lumpur	3°08'N, 101°42'E	29/09/2014– 19/11/2014 (22 days)	MJIIT	CR1, CR2, CR3, CR4, CR5, CR6	677
	UiTM, Shah Alam	3°04'N, 101°30'E	11/10/2014– 21/11/2014 (11 days)		Faculty of Mechanical Engineering	
Workspace	UTM, Kuala Lumpur	3°08'N, 101°42'E	13/4/2015–5/5/2015 (20 days)	MJIIT	M1	652
	UiTM, Shah Alam	3°04'N, 101°30'E	5/3/2015–21/5/2015 (29 days)		UiTM 1 UiTM 2 UiTM 3	
						Total 2011

Note: n: Number of sample

## **Measurement period**

For each classroom, data collection was carried out in both morning and afternoon, when students were participating in a learning activity. All materials, including the equipment and questionnaires, were prepared in the classroom twenty minutes before the start of the lecture.

Meanwhile in the university workspaces, each respondent voted up to ten times throughout the study, while the climatic variables were throughout the time the study was conducted in the work spaces; between three to ten working days at each location. During

days when environmental measurements were taken, the questionnaires were distributed twice a day; in the morning between 10:00 and 11:00, and in the afternoon between 14:00 and 15:00. Prior to data collection, respondents were briefed about their participation in the survey.

### **Field measurement method**

Field measurements include the five objective parameters: outdoor temperature ( $T_o$ ), indoor air temperature ( $T_a$ ), indoor globe temperature ( $T_g$ ), indoor air velocity ( $V_a$ ), and indoor relative humidity (RH). The instruments used in this study are as listed in Table 2. Each of the instruments was calibrated and tested before the data collection. For outdoor environmental parameters, data were obtained from the MJIIT building weather station and the Sultan Abdul Aziz Shah airport weather station.

Table 2. List of instruments used

Instrument	Parameter	Manufacturer, Country	Sensor type	Resolution	Accuracy and tolerance
Thermo recorder TR-77Ui	Air temperature	TandD, USA	External sensor	0.1°C	± 0.5°C
	Relative humidity			1% RH	± 5% RH [at 25°C, 50%]
Thermo recorder TR-52i	Globe temperature	TandD, USA	External sensor	0.1°C	± 0.3°C [-20°C to 80°C]
	Air Temperature			0.03 °C	±0.35°C [0° to 50 °C]
Thermo recorder U12-013	Globe temperature	Onset, USA	External sensor cable tmc1-hd + 40 mm black sphere		
	Relative humidity		Internal sensor	0.03% RH	±2.5% RH [10% to 90%]
Hot-wire anemometer	Air movement	Kanomax, Japan	Needle probe 6542-2G	0.01 m/s	± (2% of reading ± 0.0125) m/s [0.10–30.0 m/s]

To investigate indoor conditions, the equipment above was used measure air temperature, humidity, and air velocity. Thermo recorders in classrooms (Figure 1a and b) were paired and positioned 1.1 m above floor level by attaching them to a stand, to simulate the approximate height of a sitting person. These were placed in the corners of the room and measured  $T_a$  and  $T_g$ . For each set of measurements, instruments were left for 90 minutes with data collected at ten second intervals. In workspaces investigated, the thermo recorders (Figure 1c) were each mounted to a clamp on laboratory retort stand and placed in several points in the rooms, at approximately 1-meter radius from the respondents (Damiati *et al.*, 2016). The height of each instrument's sensors was adjusted to a height of 1.1 meters above floor level. In both classrooms and offices, the hot-wire anemometer was situated in the center of the room.

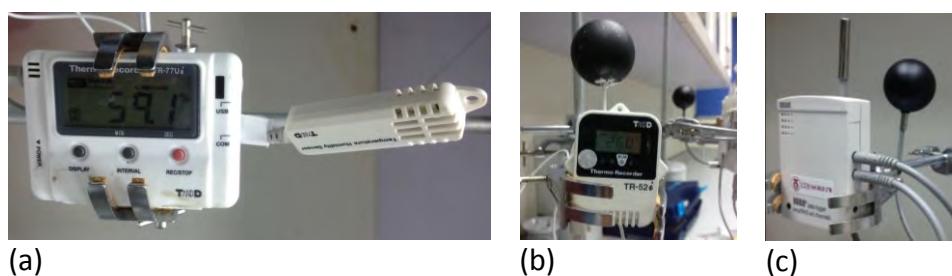


Figure 1. Thermo recorders used in field measurement: a) TR-77Ui, b) TR-52i, c) HOBO U12-013

### **Questionnaire survey**

Data on personal parameters, such as the insulation value of the occupants' clothing and their thermal perceptions, were gathered by using the questionnaires. The questionnaires were used to collect data on building occupants' thermal sensation (TSV), thermal

preference (*TP*), and overall comfort (*OC*). The questionnaires were distributed in English and Malay. The *TSV* in English questionnaire was presented using the 7-point ASHRAE scale while the Malay translation used 7-point modified thermal sensation scale (Rijal *et al.*, 2017), to allow respondents to distinguish between cool and cold, as both are described identically in Malay. A summary of the terms used, including the *TSV* scales, are shown in Table 3.

Table 3. Comparative description of questionnaire variables in English and Malay

Thermal sensation vote			Thermal Preference			Overall comfort		
Scale	English	Malaysian	Scale	English	Malaysian	Scale	English	Malaysian
-3	Cold	Sangat sejuk	-2	Much cooler	Lebih sejuk	1	Very uncomfortable	Sangat tidak selesa
-2	Cool	Sejuk	-1	Slightly cooler	Sedikit sejuk	2	Uncomfortable	Tidak selesa
-1	Slightly cool	Sedikit sejuk	0	No Change	Tidak inginkan sebarang perubahan	3	Slightly uncomfortable	Sedikit tidak selesa
0	Neutral	Biasa	1	Slightly warmer	Sedikit panas	4	Slightly comfortable	Sedikit selesa
1	Slightly warm	Sedikit panas	2	Much warmer	Lebih panas	5	Comfortable	Selesa
2	Warm	Panas				6	Very comfortable	Sangat selesa
3	Hot	Sangat Panas						



Figure 2. Thermal comfort survey in a) classroom and b) workspace (Red circles indicate the instruments)

### Analytical method

To obtain the neutral temperatures based on survey and prediction, the traditional linear regression method was performed using IBM SPSS Statistics version 22 software. For prediction results, the *PMV* and predicted percentage of dissatisfied (*PPD*) were estimated using *PMV Calculator Microsoft Excel plugin* by Tanabe and Sato (2002).

### Results and discussions

From the field measurement and survey, a total 2011 sets data on climatic parameters and questionnaire answers were gathered. The data were processed to obtain the neutral temperatures, both from *PMV* calculation and *TSV* or survey results.

#### Climatic data and questionnaire survey results

The mean value of each parameter, including thermal parameters and questionnaire results was calculated and presented in Table 4. These are separated into two broad categories; university classrooms and workspaces.

The data demonstrated that, compared to university workspaces, locations where classrooms were located experienced higher outdoor temperatures during days when measurements were taken. Despite this, indoors, the  $T_a$  and  $T_g$  between workspaces and classrooms were close enough to be identical, due to mechanical cooling used in both

spaces. The *RH* between classrooms and workspaces differ on average by 7.4%. However, the *V<sub>a</sub>* was markedly higher in university workspaces than in classrooms.

The personal parameters of respondents are also similar between university workspaces and classrooms. On average, respondents in all locations wear clothing ensembles that have similar *I<sub>cl</sub>* values. Also, in line with the identical indoor temperatures, respondents report similar *TSV* in both locations. The trend also consistent in terms of predicted votes, which is shown by similar mean of *PMV* in both classroom and workspace.

However, while the occupants in classrooms prefer no temperature change, occupants in university workspaces prefer a cooler environment, as reflected by their *TP* scores. Another measure of comfort, their thermal acceptance scores, showed that 74.1% of occupants in classrooms found the indoor thermal conditions acceptable, compared with 93.8% workspace occupants.

On the 6-point scale for overall comfort, 40.5% of the occupants in classrooms perceived themselves to be 'slightly comfortable', and 34.6% felt 'comfortable'. Meanwhile in the university workspaces, 66.7% of the admitted that they felt 'comfortable', while 19.6% felt 'slightly comfortable'. These figures show that the overall comfort level was higher in workspaces than in the classrooms. It is also evidenced by the mean *OC*, whereas the value in workspace was slightly higher by 0.6.

Table 4. Summary statistics for environmental and personal variables

Space function	Variable	<i>T<sub>out</sub></i> (°C)	<i>T<sub>a</sub></i> (°C)	<i>T<sub>g</sub></i> (°C)	<i>RH</i> (%)	<i>V<sub>a</sub></i> (m/s)	<i>I<sub>cl</sub></i> (clo)	<i>TSV</i>	<i>TP</i>	<i>PMV</i>	<i>OC</i>
Classroom (n= 873)	Mean	31.4	24.2	24.2	51.8	0.17	0.57	-0.7	0.0	-0.4	4.1
	S.D.	2.7	0.9	0.9	8.0	0.12	0.19	1.2	0.9	0.6	1.0
Workspace (n= 1115)	Mean	28.8	24.0	24.4	58.2	0.23	0.61	-0.6	-0.1	-0.1	4.7
	S.D.	1.0	1.7	1.7	5.9	0.09	0.16	1.0	0.8	0.6	0.7

*T<sub>out</sub>*: Outdoor air temperature, *T<sub>a</sub>*: Indoor air temperature, *T<sub>g</sub>*: Globe temperature, *RH*: Indoor relative humidity, *V<sub>a</sub>*: Air velocity, *I<sub>cl</sub>*: Clothing insulation value, *TSV*: Thermal sensation vote, *TP*: Thermal preference, *PMV*: Predicted mean vote, *OC*: Overall comfort vote, *n*: Number of sample, *S.D.*: Standard deviation

### PMV and PPD

*PMV* and *PPD* were estimated based on the six parameters measured through field surveys; *T<sub>a</sub>*, *T<sub>mrt</sub>*, *RH*, *V<sub>a</sub>*, *I<sub>cl</sub>*, and metabolic rates. The results of these estimations are plotted on the *PMV* and *PPD* equation curve. Each figure also includes a plot of the actual data; actual percentage of dissatisfied (*APD*) against mean *TSV* in each session on a separate graph. To ease comparative analysis, both graphs are drawn at the same scale. For the purpose of this study, *APD* is defined as the percentage of respondents in a given session voting for either +2, +3, -2, or -3 on the 7-point *TSV* scale.

Analysis in this study is performed separately for university classrooms and workspaces. For classrooms, each point in Figure 3 represents the mean *TSV* for one measurement session. A projection line was illustrated in each graph, by calculating *PPD* of all range of *PMV* from -3 to 3, then connecting them through a spine line. From the comparison between predicted and actual results, the latter is more scattered than the former. Amongst occupants in UTM lecture rooms, both calculated *PMV* and actual *TSV* lay between the values of 2 and 1. However, in UiTM the maximum recorded mean *TSV* was neutral (0), and some *PMV* had negative values. Figure 3 also shows that *TSV* of <-1 are often observed, indicating that occupants in these air-conditioned classrooms often felt cold.

Because more data is available from university workspaces, the data also exhibit a wider range. Some *PMV* results from UiTM workspaces, as shown in Figure 4, were calculated to be less than -1, corroborating the actual measurement results. However, the

*PMV* results also overestimate warm sensations – while one session was predicted to have a *PMV* of +2, the actual mean *TSV* was -1. This manifests throughout the whole dataset for workspaces, where a *PMV* of 0 corresponded to a *TSV* of -1.

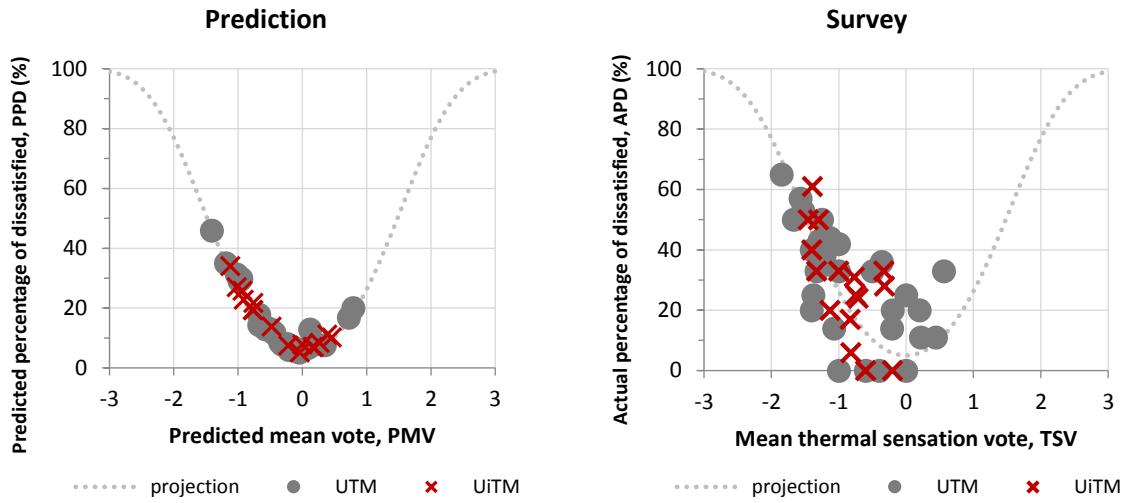


Figure 3. Mean thermal sensation vote and percentage of dissatisfied in university classrooms, each point represents mean vote from respondents in a single measurement session

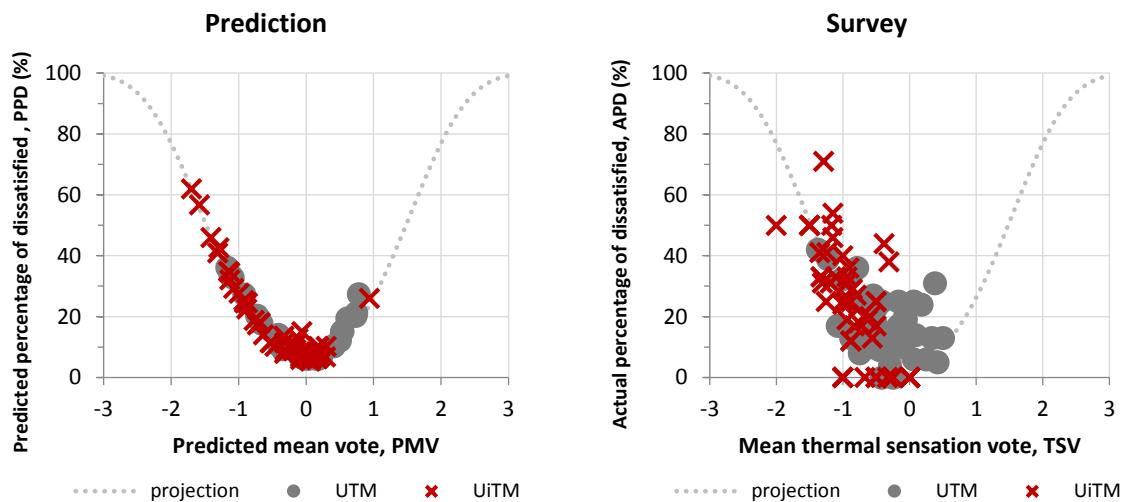


Figure 4. Mean thermal sensation vote and percentage of dissatisfied in university workspace, each point represents mean vote from respondents in a single measurement session

### Neutral temperature

The neutral temperature for occupants in all investigated locations were calculated using linear regression analysis of *TSV*, *PMV*,  $T_a$  and  $T_g$ . Data between universities were combined but was delineated between classrooms and workspaces. Figure 3 plots these regressions against *PMV* and *TSV*. It can be seen that in both classrooms and workspaces, *PMV* overestimates the neutral temperatures at higher temperatures. The gap between actual and predicted results increase as the temperature increases. The results of the linear regression analysis are presented in Table 5.

Despite the uniformly low  $R^2$ , all *TSV* regressions are statistically significant at the 0.001 level. *PMV* regressions have higher  $R^2$ , but predict lower neutral temperatures compared to *TSV* regressions. *PMV* regressions predict neutral temperatures of 24.5°C and 24.8°C  $T_a$  in university workspaces and classrooms respectively. In comparison, *TSV*

regressions predict temperatures of  $27.1^{\circ}\text{C}$  and  $26.2^{\circ}\text{C}$   $T_a$ . The calculated neutral temperatures are similar between  $T_a$  and  $T_g$  results, with only  $PMV$  in workspaces showing a difference of  $0.3^{\circ}\text{C}$  between these results. In comparison to these neutral temperatures, the comfort temperatures calculated using Griffiths' method (Griffiths, 1990; Rijal *et al.*, 2015; Damiati, 2017) with 0.5 as the constant showed mean values in between survey and prediction results in all locations. The Griffiths' comfort temperatures were higher than predicted results but still lower than the regression neutral temperatures based on survey data.

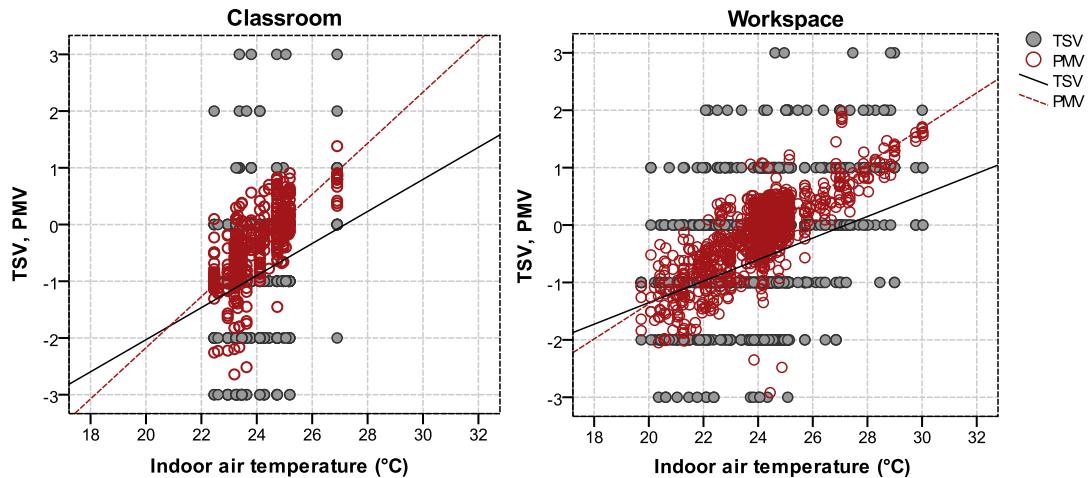


Figure 5. Regression graphs of  $TSV$  and  $PMV$  against indoor air temperature in classrooms and workspaces

Table 5. Neutral temperature regression analysis

Space function	$n$	Thermal indices	Case	Regression Model	$R^2$	$T_n$	S.E.	$p$	$T_c$
Class-room	873	$T_a$	Survey	$TSV = 0.350 T_a - 9.176$	0.06	26.2	0.046	<0.001	25.6
			Prediction	$PMV = 0.450 T_a - 11.169$	0.50	24.8	0.022	<0.001	(s.d.: 2.4)
	1114	$T_g$	Survey	$TSV = 0.331 T_g - 8.735$	0.06	26.4	0.044	<0.001	25.6
			Prediction	$PMV = 0.438 T_g - 10.887$	0.47	24.9	0.022	<0.001	(s.d.: 2.4)
Work-space	1114	$T_a$	Survey	$TSV = 0.188 T_a - 5.104$	0.09	27.1	0.018	<0.001	25.2
			Prediction	$PMV = 0.306 T_a - 7.497$	0.65	24.5	0.007	<0.001	(s.d.: 2.3)
		$T_g$	Survey	$TSV = 0.202 T_g - 5.506$	0.11	27.3	0.018	<0.001	25.5
			Prediction	$PMV = 0.309 T_g - 7.670$	0.66	24.8	0.007	<0.001	(s.d.: 2.2)

Note:  $T_a$ : Indoor air temperature ( $^{\circ}\text{C}$ ),  $T_g$ : Indoor globe temperature ( $^{\circ}\text{C}$ ),  $n$ : Number of sample,  $TSV$ : Thermal sensation vote,  $PMV$ : Predicted mean vote,  $T_n$ : Regression neutral temperature ( $^{\circ}\text{C}$ ), S.E.: Standard Error,  $p$ : Significance level of regression coefficient,  $T_c$ : Griffiths' comfort temperature ( $^{\circ}\text{C}$ ).

These neutral temperature results based on questionnaire survey are higher compared to a previous study in the same university workspace, which calculated a comfort operative temperature of  $25.6^{\circ}\text{C}$  using the Griffiths' method (Damiati *et al.*, 2016). The results are also comparatively high against another study in air conditioned university classrooms in Indonesia (Karyono *et al.*, 2015), which calculated neutral temperatures of  $24.9^{\circ}\text{C}$   $T_a$  and  $23.3^{\circ}\text{C}$   $T_g$  using similar regression method as applied in this study.

## Conclusions

Based on the results of this study of two universities in Malaysia from 2013 to 2014, the following conclusions can be drawn:

1. Using the  $TSV$  values obtained using questionnaires, the neutral temperatures of university workspaces were calculated to be  $27.1^{\circ}\text{C}$   $T_a$  and  $27.3^{\circ}\text{C}$   $T_g$  while the neutral temperatures of classrooms were  $26.2^{\circ}\text{C}$   $T_a$  and  $26.4^{\circ}\text{C}$   $T_g$ .

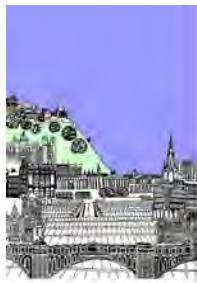
2. Using the *PMV* values calculated using the environmental variables, the neutral temperatures of university workspaces were calculated to be 24.5°C  $T_a$  and 24.8°C  $T_g$  while the neutral temperatures of classrooms were 24.8°C  $T_a$  and 24.9°C  $T_g$ .
3. Comparisons between the actual and predicted results show that *PMV* underestimates comfort temperatures at higher temperatures. Therefore, alternative thermal comfort analytical method based on questionnaire surveys, e.g. regression and Griffiths' method, are recommended for suitability in hot-humid climates such as in Malaysia.

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### References

- Astolfi, A. and Pellerey, F. (2008) Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms. *The Journal of the Acoustical Society of America*. 123 (1), 163–173.
- Clements-Croome, D. (2001) Influence of social organization and environmental factors and well-being in the office workplace. In: *Proceedings of CLIMA 2000 world congress*. 2001 Naples. p.
- Corgnati, S.P., Filippi, M. and Viazzo, S. (2007) Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Building and Environment*. 42 (2), 951–959.
- Damiati, S.A. (2017) *Thermal comfort field study in office buildings with different ventilation modes in hot and humid conditions*. Universiti Teknologi Malaysia.
- Damiati, S.A., Zaki, S.A., Rijal, H.B. and Wonorahardjo, S. (2016) Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season. *Building and Environment*. 109208–223.
- Griffiths, I. (1990) *Thermal comfort in buildings with passive solar features: Field studies*.
- Karyono, T.H., Heryanto, S. and Faridah, I. (2015) Air conditioning and the neutral temperature of the Indonesian university students. *Architectural Science Review*. 58 (2), 174–183.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*. 15 (3), 259–263.
- Rijal, H.B., Humphreys, M.A. and Nicol, F. (2015) Adaptive Thermal Comfort in Japanese Houses during the Summer Season: Behavioral Adaptation and the Effect of Humidity. *Buildings*. 5 (3), 1037–1054.
- Rijal, H.B., Humphreys, M.A. and Nicol, J.F. (2017) Towards an adaptive model for thermal comfort in Japanese offices. *Building Research & Information*.
- Saidur, R. (2009) Energy consumption, energy savings, and emission analysis in Malaysian office buildings. *Energy Policy*. 37 (10), 4104–4113.
- Tanabe, S. and Sato, T. (2002) *PMV Calculator*. [Online]. 2002. Waseda University Research Laboratory.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Influences of Building and Urban Typologies on the Study of Thermal Comfort in 'Shophouse' Dwellings in Ho Chi Minh City, Vietnam

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**Abstract:** The 'Shophouse' is a repetitive form of vernacular residential building type found in Vietnam and Southeast Asia. The main mechanism for controlling the indoor environment of most shophouses across Vietnam is natural ventilation. However, under the pressures of climate change and rapid urbanisation, the indoor thermal conditions of shophouses have become uncomfortable for occupants. Consequently, demand for cooling energy is increasing year-on-year. This paper presents the classification of architecture and urban typologies of shophouses and their subdivisions along with key characteristics found in Ho Chi Minh City, Vietnam. The studies of thermal environment in shophouses identified that thermal conditions varied in a partially systematic way when classified according to building and urban typologies. They also showed the indoor environment in row houses of new residential communities is more comfortable than other types. The comparison of thermal performances in the shophouses indicates a relationship between comfort and energy expenditure for the building/urban typologies across the city. The understanding of the thermal performance of different shophouse typologies and their urban structure types significantly contributes to the development of policies and standards for shophouse construction and planning to optimise comfort and energy efficiency.

**Keywords:** Shophouses, urban & building typology, thermal comfort, indoor environment, Vietnam.

### Introduction

The impacts of climate change and massive urbanisation is accelerating pressure on housing resources and planning, living environments, and energy use in Vietnam, especially in high dense cities such as Ho Chi Minh City (HCMC). In 2010, a total of 5.6million sqm of residential floor area was provided and by 2020, the prediction is for 6.5million sqm (CPHSC, 2010). However, the prediction is likely to be an underestimate. In 2010, a project undertaken by the University of Cottbus concluded that the total coverage area of dwellings was 445.6 km<sup>2</sup> accounting for 21.1% of the total HCMC area (Downes & Storch, 2014). Furthermore, along with influences of climate change, the occupants' living environment is very vulnerable to discomfort because most houses in the city have so far used only natural ventilation to dissipate heat and humidity. Thus, recently there has been an increase in installation and use of air conditioning. The high density of the city and the increased use of air-conditioning and other domestic electric appliances is adding to the heat island effect. Based on observation and prompted by the studies of the University of Cottbus, the building and urban typologies around HCMC were analysed and classified. Such knowledge helps understand the adaptation of the city to climate change, and also thermal comfort and energy use in buildings, particularly dwellings. This paper focuses on analysing thermal environment and energy consumption of

'shophouses' corresponding to their building and urban typologies. The paper examines the relationship between architectural and urban characteristics based on the 'shophouse' and indoor thermal performance as well as occupant behaviours.

## Background

### *Climatic conditions in HCMC*

Ho Chi Minh City is located in the south of Vietnam. The local climate is strongly influenced by monsoon winds that create hot humid condition throughout the year. The annual average temperature is around 28°C and is the warmest in March, April and May. The daily air temperature range is from 22°C to 35°C with two distinct seasons – dry (December to April) and wet (May to November). The annually average seasonal relative humidity varies from 63% to over 80%. South and south-east monsoon winds are dominant in dry months with a maximum air velocity of 4.5m/s; in contrast, the prevailing winds from the west and south-west are very strong in the rainy months reaching 5m/s (Institute of Science, 2009). The availability of natural winds has an impact on occupant comfort and promotes the use of natural ventilation to reduce the need for air-conditioning.

### *The housing stock in HCMC*

There has been rapid urbanisation in HCMC with the urban population in 2015 estimated to be over 8m and a prediction to reach 10m in 2020; a doubling compared to 1999 levels (CPHSC, 2010) (DEMOGRAPHIA, 2015). The population explosion has resulted in a crisis of housing resources, residential planning policies, and control of the real estate market. The settlement coverage of HCMC has more than doubled during the last 20 years (Storch & Downes, 2011). Along with managing these issues, it is also necessary to address climate change, comfort and energy use.

Table 1 Numbers of floor area (sqm) by housing types in HCMC in 2009 (source: adapted from CPHSC, 2010)

	Single/Detached house	Apartment	Not stated	Total
Entire city	165,454,187	5,199,874	1,981,009	172,635,070
Urban	138,474,954	5,064,224	1,875,999	145,415,177
Rural	26,979,233	135,650	105,010	27,219,893

The housing stock in HCMC has three main groups: 'shophouses', villas, and apartments, in which, the 'shophouse' building type is predominant. The Vietnam Census of 2009 indicated that approximately 96% of the population lived in single/detached houses in HCMC. Such single properties were the preference of occupants in both urban and rural areas (Table 1). Additionally, the density of separate dwellings is much more predominant in urban regions than in the periphery. The research of Dam (2011) and Le (1999) has discovered why 'shophouses' are the most popular dwelling typology. 'Shophouses' began to appear in HCMC during French rule in the colonial period. Many streets of row houses were constructed for low-income families to create a trading environment for Western and Asian products. These row houses provided both living space and economic benefits for the householders and this attracted people to move to the city increasing population density in what evolved to be 'shophouses'.

### *Energy use for cooling in Vietnam and HCMC*

A country-wide survey of 1,394 houses by Cimigo's group (Parkes, 2013) and Census of Vietnam in 2009 has shown the energy demand of households to be associated with housing

type and urban area. The energy use of 'shophouses' accounted for 69% of total expenditure by all dwellings in 2013. An average household paid around 606,142VND (23GBP) for a monthly electricity bill accounting for 11% of mean monthly household expenditure; however, in the hotter months, the householders paid more for cooling by mechanical systems. In addition, the Cimigo's team assessed all devices providing comfort for users (such as such as ceiling/standing/wall mounted fans and air-conditioners) through nationwide online surveys. The survey concluded 48% households owned air-conditioning units and 45% households used fans. Another survey by Dream Incubator in 2015 for 1,554 houses found 1,165 dwellings owned at least of one air-conditioner with the number linked to the economic situation of each household. However, recent increases in electricity costs and changes in attitude of people towards a more environmentally friendly lifestyle have influenced preference for using natural ventilation to remove heat. In 2013, 79% of 1,394 households surveyed, preferred opening windows to capture natural ventilation for cooling even though mechanical cooling systems still had advantages.

## **Methodology**

For research objects, twenty 'shophouses' including different housing and urban typologies, and city zones in HCMC were visited for this study. Most of the case studies were found to be hybrid and non-air-conditioned houses. Cooling by use of air conditioners has been applied for the warmest months whilst fans are usually used over the year. The features of building architecture (a number of rooms/floors, characteristics of windows/doors/openings), ventilation/cooling systems and demographics of every household were collated.

For the time of observations, depending on the analysis of local climate, the empirical studies were conducted in May (hot month) and September (cool month) in 2015 and 2016.

For climatic measurements, four environmental indices including air temperature, air velocity, relative humidity, and lighting were recorded for indoor and outdoor 'shophouses'. A multi-functionally environmental meter was used to measure relative humidity and lighting level. Besides, the thermal and airspeed values were collected by a hot wire anemometer probe. The indoor climatic measurements were held at the same single height of 0.8m above the floor and in regarding the instructions of ASHREA Standard 55; however, in which, wind velocities of indoor air were difficult to measure. The on-site investigation helps understand the impacts of the outdoor environment on comfort in naturally ventilated residences. After the surveys, the analysis took place to try to establish the relationship between the indoor thermal conditions of 'shophouses' linked to their architecture, housing typology and their location in the city.

## **Building and urban typologies of 'shophouses'**

### ***Definition of the 'shophouse'***

A 'shophouse' is an individual house that has a particular settlement pattern including both 'shop' (on a busy commercial street) and 'house' (providing accommodation). Across Vietnam, the 'shophouse' type account for 75% of all houses. Streets of 'shophouses' began to form during the last hundred years, particularly in 36 Old Quarters in Hanoi, in an ancient town in Hoian, and in Cho Lon in HCMC. They are a flexible combination of spaces for accommodation and business (Le, 1999) and exhibit diverse forms of façades.

The principal characteristic of a ‘shophouse’ dwelling is the shape of the house. It is very long and narrow as a tube, so they are also known as ‘tube houses’. The width is generally 3m to 5m and the length may vary from 20m up to 50m, even 100m. ‘Shophouses’ can comprise one storey or more up to a maximum of five. All ‘shophouses’ are allocated along, and perpendicular to, streets and alleys. Thus, people can approach at the main façade of buildings from road or alley. For planning of a residential neighbourhood, the ‘shophouse’ land plots are divided both regularly and irregularly. The land coverage of ‘shophouses’ in core districts of the city can be up to 100%; meanwhile, in lower dense regions, the land cover is up to 80%. The ground floor is normally used to run a family business or it is rented out; accommodation for occupants is organised on upper floors.



Figure 1 ‘Shophouse’ dwelling density (a) & typical traditional ‘shophouse’ (b) in Cho Lon, District 5, HCMC



Figure 2 Diversiform facades of a street by combining individual ‘shophouses’ in Cho Lon

### ***Classification of building typologies based on ‘shophouses’***

The ‘shophouses’ in HCMC were first built by the Chinese, Singaporean and Indian inhabitants located in districts 1 and 5. These have become known as the ‘traditional shophouses’ (see Figures 1 and 2). The typologies have changed significantly due to economic and population growth, and local trends. The five common ‘shophouse’ typologies in HCMC are rudimentary, ‘traditional’, ‘new’, ‘commercial’, and ‘row’ house (see Figure 3). Individual building types have distinct physical characteristics of the material, building volume, usage, access and design solutions. For example, the new ‘shophouses’ which are the most popular dwelling type usually appear in the compact area of the city. They have a wide variety of building size, façade appearance, architectural style and a number of floors. Whilst, the row houses popularly contain three to five storeys; their form and architecture commonly start from an archetype determined by preserving the unity of a whole street. Block types can be single mixed creating a unique characteristic for each neighbourhood. Three popular housing types A2, A3 and A5 were used in this study.

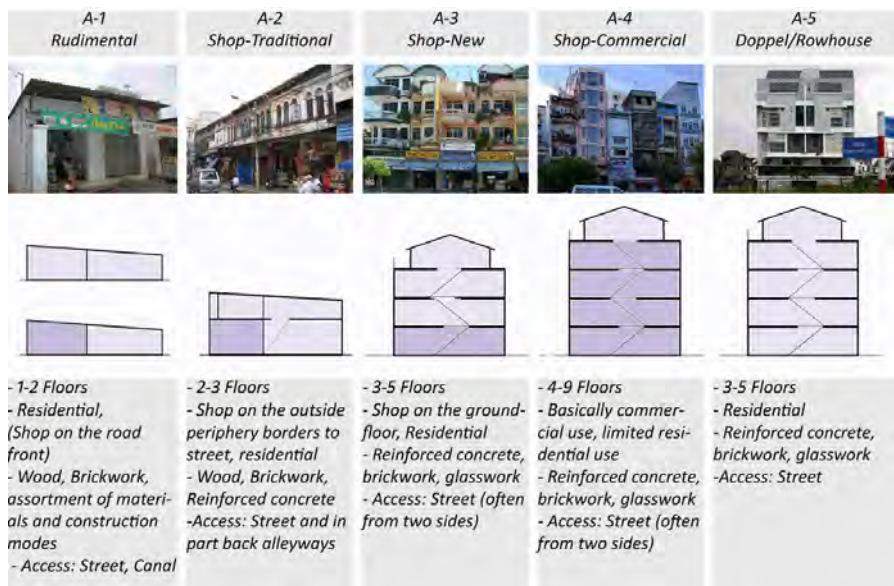


Figure 3 'Shophouse' building typologies in HCMC (source: Downes & Storch, 2011)

### **Classification of urban typologies based on 'shophouses'**

The University of Cottbus used land-use maps and on-site investigation, to classify the urban structure type and building type for a number of urban blocks in 2010. A total of 82 discrete urban structure typologies were identified covering 16,292 blocks (Downes & Storch, 2014). Twelve 'shophouse' urban typologies covering 42,311 ha area of HCMC were characterised by the ratio of construction density and planning method; five of these divided into three groups were selected for the survey based on coverage, problems related to comfort environments, housing management, construction, and energy.

Table 2 Summary of urban structure types of 'shophouses' (source: adapted from Downes & Storch, 2014)

Type	'Shophouse' category	No of blocks	Build. ratio	Surface area (ha)
01	Regular new (111)	100	70	450
02	Regular new community (112)	62	60	392
03	Regular + narrow street (113)	592	75	2,063
04	Regular + yards (114)	153	44	2,020
05	Irregular high density (121)	425	78	1,602
06	Irregular + yards (122)	794	57	4,444
07	Irregular scattered	815	28	6,990
08	Irregular clustered	741	30	5,490
09	Irregular +large gardens	2,342	5	17,133
10	Irregular temporary			85
11	Shophouse + industry	222	74	1,292
12	Shophouse irregular & regular	23	69	350

Table 2 shows the different groups of shophouses. Group 1 (types 01 and 02) contains terrace archetypes located perpendicular to main streets in a back-to-back pattern, and with communal spaces within each residential block. Secondly, Group 2 (type 03) is regular with a narrow street/alley and is composed of low to high-rise shophouses oriented to the main street/alley. The building density of this group is much higher than group 1. Group 3 (types 05 and 06) is a high-density style with narrow streets. The characteristic of these types is their inhomogeneity and lack of planning; they are located along the outer edges of main streets.

## Results and discussion

### *Environmental performance*

Generally, the record of average air temperatures according to city/urban/building typologies of 'shophouses' showed warm indoor and outdoor conditions in both hot and cool seasons with the hot season being typically 3°C warmer than cool. The typical variation between indoor and outdoor values was 1°C. In ASHRAE 55-2004 standard, the neutral temperature is defined at 24°C and its' extension for the occupants in the tropics is 1°C more (Brager & Dear, 2001) (ASHRAE, 2004). However, these measured figures in HCMC are 7°C to 10°C higher than the standard's recommendation. Furthermore, the high temperatures have an impact on the relative humidity in hot and warm climates (Nicol, 2004).

The deviation of relative humidity between two seasons was 11%. In hot months, the mean relative humidity levels were lower than in cool months (see Table 3). Based on a meta-analysis of Nicol (2004) from 25 worldwide field surveys in hot-humid condition, higher humidity will be a barrier for comfort due to decrease evaporative heat loss in the hot thermal environment. This means that the effect of air movement acts a play to balance between two features of air temperature and humidity. The analysis also showed that provision of air movement of 0.4m/s may be beneficial to increase 2°C more in comfort temperature but observations of the field study in HCMC performed that the indoor wind environment was poor in the hot condition. It is clear that careful attention and understanding is needed to choose an optimum design and that building and urban typology may have an impact.

Table 3 Climatic environment indoor/outdoor 'shophouses' following city/urban/building typologies

Category	Indoor				Outdoor			
	Cool season	Standard deviation	Hot season	Standard deviation	Cool season	Standard deviation	Hot season	Standard deviation
Air temperature °C	31.7	0.8	34.3	0.5	32.3	1.7	35.4	1.2
Relative humidity %	70	7	59	5.5	68	6.5	56	5
Airflow m/s			0.2	0.15			0.6	0.35

Initial monitoring was carried out to examine if specific features of urban and building typologies affect the thermal performance inside and outside the houses sufficiently to be characterised according to type and season. Table 4 shows the environmental conditions measured in the hot season (May) for the different urban typologies. Variations can be seen for instance the air temperature in blocks of type 5 & 6 was the hottest at 36.4°C. Meanwhile, the airflows outside were lower. These analyses show that the planning of residences among a housing block might affect to the microclimatic conditions outdoor the houses.

Table 4 In-situ investigation of environmental condition of the shophouses in HCMC in hot season

Shophouse' urban type	In. Temp	St. Dev.	Out. Temp	St. Dev.	In. RH	St. Dev.	Out. RH	St. Dev.	In. airflow	St. Dev.	Out. airflow	St. Dev.
Type 1 + 2	33.8	0.4	34.2	0.4	62	6	61	3	0.3	0.16	0.8	0.2
Type 3	34.7	0.3	34.9	0.1	54	4	52	5	0.4	0.1	0.5	0.1
Type 5 + 6	34.3	0.4	36.4	1.1	59	4	55	2	0.16	0.13	0.6	0.45

Measurements of indoor temperatures in the 'shophouses' of all five urban types averaged over 33°C while the effect of air movement was not limited. According to Szokolay (1997), occupants can find comfort in air speeds from 0.25-0.5m/s. However, the observations and measurements on-site showed that airflow over 0.25m/s was

inconsistent in all case studies. The air movement in spaces of 'shophouses' of lower density housing areas seemed more beneficial in comparison. In addition, in the hot conditions in the tropics, the presence of air movement can be sufficient to compensate for the equivalent of 4°C if the air movement reaches at 1m/s (Nicol, 2004). Based on the evidence collected, natural ventilation alone would be insufficient to provide comfort in the 'shophouses' leading to increased demands for mechanical cooling.

Table 5 The environmental conditions indoor and outdoor shophouses according to housing types

'Shophouse' type	In. temp	St. Dev.	Out. temp	St. Dev.	In. RH	St. Dev.	Out. RH	St. Dev.	In. airflow	St. Dev.	Out. airflow	St. Dev.
New shophouse	34.3	0.5	35.7	1.2	59	6	55	5	0.15	0.11	0.54	0.34
Row house	34.0	0.1	34.3	0.4	59	5	59	1	0.4	0.12	0.95	0.17

A further examination of environmental conditions comparing row houses with new 'shophouses' is shown in Table 5. This would suggest row houses be more comfortable and showing improved air movement potential inside and outside. The more compact buildings seem to be associated with poorer microclimate environments. Outdoor temperatures around new 'shophouse' are significantly higher though indoor air temperatures are similar.

### Adaptive behaviours

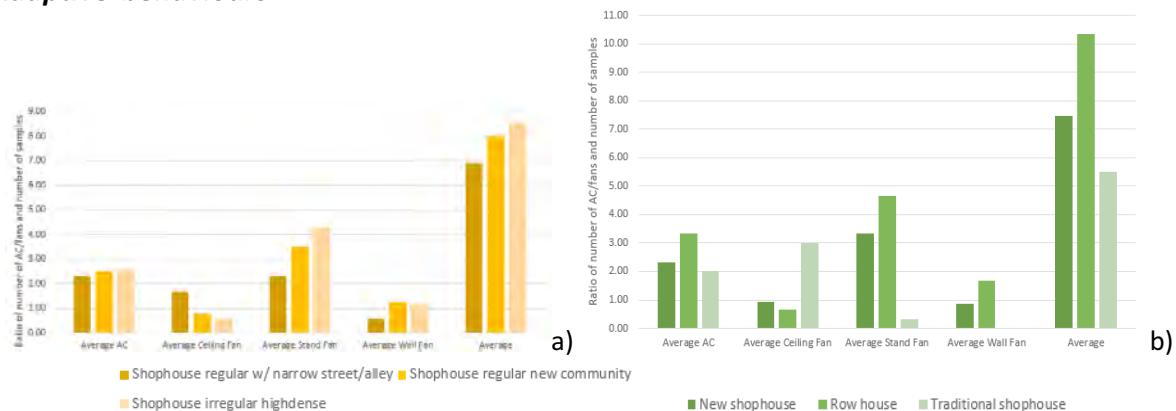


Figure 4 Preference of households for cooling systems following urban (a) and building (b) typologies

Both internal and external environmental conditions, especially in hot months have impacts on the adjustments of occupants in using mechanical ventilation and air conditioning to compensate for heat discomfort. However, the income and lifestyle of each household affect the preference of householders to utilise standing fans, wall mounted fans, ceiling fans or air conditioners. Figure 4 shows the occupants' choices as percentage use of systems for different urban and building types. In both categories, the use of air conditioning has become more popular as well as utilisation of standing fans. A comparison electrical energy use for all ventilated devices used in the three urban typologies shows the demand of 'shophouses' in irregular high-density regions to be the most. Assessing the frequency of use of air-conditioners produces a slightly different result whilst the use of fans is the main preference to deal with less extreme conditions. Figure 4b indicates that the users in row houses are using the most electrical cooling of the three 'shophouse' types. This might be attributed to the needs of modern life and construction regulations in new residential communities around the city. In contrast, all fan types are preferred for use in the new and traditional houses.

## **Conclusions**

Dwellings of a repetitive terrace type found in Vietnam are known as 'shophouses'. These houses are long and thin and represent more than 95% of the housing stock in HCMC. The impacts of global warming and urbanisation influence on the occupants' comfort are increasing causing heat stress and thermal discomfort. The classification of 'shophouses' according to urban and building types in a systematic way in HCMC significantly contributes to improving the study of thermal conditions and comfort in houses around the city. In the majority of free-running 'shophouses' in HCMC, the thermal environment is less comfortable for the occupants due to high indoor air temperature whilst the effect of natural airflows is not sufficient to compensate. So, a trend of using mechanical ventilation becomes popular for the householders to maintain thermal comfort. The results of field study perform that the thermal environment in the 'shophouses' in blocks of group 1 was more relieved while the indoor and outdoor wind environment also showed more potential for natural cooling to remain the comfort. The initial outcomes of this research indicate the potential for better planning and design of 'shophouses' and their residential neighbourhoods to provide a beneficial thermal environment and encouragement of natural ventilation to reduce discomfort and energy use for cooling.

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## **References**

- ASHRAE, 2004. *ASHRAE Standard 55-2004: Thermal environmental conditions for human occupancy*. Atlanta GA: ASHRAE Inc.
- Brager, G. & Dear, R. d., 2001. *Climate, Comfort & Natural ventilation: A new adaptive comfort standard for ASHRAE Standard 55*. Oxford, Oxford Brookes University.
- CPHSC, 2010. *The 2009 Vietnam population and housing census: completed results*. Hanoi: Statistics Publishing House.
- Dam, K. H., 2011. *The urban street house - History and development trend in Vietnam urban context*. Master. The Ho Chi Minh City University of Architecture.
- DEMOGRAPHIA, 2015. *Demographia world urban areas: 11th Annual edition*, Chicago: Wendell Cox Consultancy.
- Djamila, H., Chu, C.-M. & Kumaresan, S., 2013. Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia. *Building and Environment*, Volume 62, pp. 133-142.
- Downes, N. K. & Storch, H., 2014. *The urban structure types of Ho Chi Minh City, Vietnam*. Cottbus & Ho Chi Minh City: Cottbus, Brandenburgische Technische Universität.
- Feriadi, H. & Wong, H. N., 2004. Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings*, Volume 36, pp. 614-626.
- Humphreys, M., 1978. Outdoor temperature and comfort indoors. *Batiment International, Building Research and Practice*, pp. 92-105.
- Institute of Science, 2009. *Vietnam Code 02: Vietnam building code natural physical & climatic data for construction*. Hanoi: Construction Register.
- Karyono, T. H., 2000. Report on thermal comfort and building energy studies in Jakarta-Indonesia. *Building and Environments*, Volume 35, pp. 77-90.
- Le, M. T. T., 1999. *The form and development of the urban street houses at the moment*. Master. The Ho Chi Minh City University of Architecture.
- Nicol, F., 2004. Adaptive thermal comfort standards in the hot-humid tropics. *Energy and Buildings*, Volume 36, pp. 628-637.
- Parkes, M., 2013. *Vietnam residential energy use*, s.l.: Cimigo.
- Storch, H. & Downes, N., 2011. *The dynamics of urban change in times of climate change – The case of Ho Chi Minh city*. Essen, CORP, pp. 977-984.
- Szokolay, S., 1997. *Thermal comfort in the warm humid tropics*. Brisbane, The University of Queensland, pp. 7-12.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainability and Energy Efficiency of the health facilities in a city in southern Brazil: an exploratory study

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**Abstract:** The main objective in this project has been to perform exploratory analysis on data related to the energy and water consumption of the health facilities in São Bento do Sul city, a city located in southern Brazil. A building must be sustainable and operate as economically as possible. Changes in conducting constructive processes must arise from the public sector, redirecting technological choices and investments in the sector, in order to decrease energy consumption, thus, stimulating a more sustainable behaviour of the society arising from public policies. This city features a damp climate with huge temperature variations in summer and winter. The variation in energy consumption and its connection to the local temperature and water consumption were evaluated, and consider sustainability, the correlation between water and energy consumption was evaluated. The partial results from collected data revealed no connection to the energy and water consumption variable. A considerable increase in the electric energy consumption occurs in the colder months, justified by the increased usage of heaters.

**Keywords:** Energetic Efficiency, Electric Energy, Health Facilities, Sustainability, and Water Consumption.

### Introduction

Sustainability has been increasingly challenging to the public sector. One of the greatest challenges related to sustainability is directly linked to the issue of energetic efficiency. As well as employing efficient technologies and more effective usage of natural resources are public policies required for redirecting technological choices and investments in the sector, as well as the consumers' behaviour (Menkes, 2004).

In the opinion of Lamberts et al (2014), energetic efficiency, in architecture, can be understood as an inherent attribute to the building represented by its potential to provide thermal, visual, and acoustic comfort and to users, lower energy consumption. Therefore, one building is more energetically efficient than another, when it provides the same environmental conditions, yet with lower energy consumption.

Sustainability in civil construction means to "dedicate the a great deal of attention to physical, environmental, energetic, and the technological resources of our planet and issues

related to efficiency in constructive processes, in order to bring about the smallest possible impact on the environment and individuals" (Manfron et al, 2006, p. 2).

Regarding this, buildings must be conceived in such a way as to avoid exaggerated consumption (Brasil, 2011). Therefore, the rational use of electric energy must be featured in conservation and the efficient usage of natural resources in buildings, thereby cutting down on wastes and impacts on the environment.

Procel – The National Program for Electric Energy Conservation was instituted, supervised by the Ministry of Mines and Energy – MME in 1985, a government program. Executed by Eletrobrás (the company controlling the majority of the electric energy transmission and generation system in Brazil), promoting the efficient usage of electric energy and combating waste (Procel, 2017).

According to the Ministry of Mines and Energy - MME (2016), the Electric Energy Conservation Program – PROCEL, in 1997, structured the sub-program for public buildings in order to promote initiatives for energetic efficiency for that type of building, defining the following objectives: cut down on public building expenses through reducing consumption and demand for electric energy; enhance working conditions, comfort, and safety of civil servants; qualify administrators and workers in public building in energetic efficiency. The building is designed, in such a way as to make the climate suitable, to assure the reduction of energy consumption in the phase after the building is occupied.

The "Technical Quality Regulation for Energetic Efficiency of Commercial, Service, and Public Buildings" – RTQ-C went into effect in Brazil in 2009. The document was revised in 2010, making it possible to evaluate a building by a prescriptive method or computational simulation, classifying its performance and systems (envelopment, illumination, and air conditioning) ranging from level "A", as most efficient, to "E", as least efficient" (Brasil, 2010). According to the standard guideline from the Ministry of Budget Planning and Management – MPOG (2014), labeling is still optional for the majority of building types, but it is already mandatory for new federal public buildings over 500m<sup>2</sup> or those which have been retrofitted.

The increase in individual water consumption has been verified regarding water consumption, especially in large urban centres. These are already facing problems in shortages and economic effects, due to great distances from wellsprings and the need for more accentuated water treatment arising from water pollution. Rational water usage implementation has been a choice made in large urban centres as a way to avoid losses and minimize problems related to scarcity of sources of water supply (Marinho, 2007). The issue on water shortage is so urgent people think that by 2050, around 75% of the world population may face potable water scarcity (Chen and Chen, 2016).

Historically, public administrations have placed the theme of electric energy as foremost and water in the background, considering it does not promote visibility during the inauguration of a civil construction site. When public bodies invest resources for the expansion and renovation of construction sites, energetic efficiency planning is not considered, as expenses on electric energy and water are part of institutional costs.

Thus, the obtained savings are not returned to the same entity and discourages public administrators. However in order to achieve success in energetic efficiency programs, the involvement and collaboration of all stakeholders is necessary, in public sectors, as well as private (Silva, 2015).

## **Objective**

The objective of this article has been to evaluate electric energy and water consumption in the Healthcare Units in the city of São Bento do Sul. These research studies have focused on the joint interaction between water and energy usage, which has increased substantially in the past few years (Zhang and Vesselinov, 2016), for the purpose of understanding the complex interdependence between water and energetic resources, and, as a result, improve management practices for the conservation of both resources (Vieira and Ghisi, 2016).

The city is located in northern Santa Catarina State, Latitude 26° 15' 01"S, Longitude 49° 22' 43" W, at 838 m altitude. As the climatic conditions and altitude are similar to the city of Curitiba, it can be classified as Bioclimatic Zone 1, according to NBR (Brazilian Standard) 15220-3 (ABNT, 2005), whereas the thermal conditioning strategies must employ solar heating in buildings and heavy-duty internal insulation wall seals.

## **Method**

Gil (1994) classifies research studies based on their objectives and, based on these, this specific study is classified as a descriptive research study, since its objective has been to describe the characteristics of a defined population or phenomenon or, thus, the establishment of relationships among variables.

Also, according to the author, the experimental design, as well as diagramming must be involved regarding the predictive analysis and interpretation for the data collection. Data collection is the most significant element for the experimental design. As the nature of the sources are materials, which have not yet undergone analytical treatment or they can still be reworked according to the subjects in the research study. Documentary research was used in this study. The sampling process is not probabilistic for convenience sake, as the sampling units were selected from accessible data for performing this research study.

Data was obtained from the Internal Control Sector at the São Bento do Sul City Hall. 19 of the existing 20 Healthcare Units in the City supplied data on electric energy and 16 Units from water bills, from 2013, 2014, 2015, and 2016, considering the data from 2016 includes only up to the month of September. Among the 16 Healthcare Units, only four are connected to the sewage system network.

The analysis was performed based on the sum of monthly consumption, from electric energy as well as water, from the 16 Healthcare Units, from 2013 to 2016. We choose not to include the other units in the analyses, for the purpose of maintaining the same sampling group, thereby avoiding any possible distortions in the data analyses.

The *software R program* (R Core Team, 2016) with the *R-Studio* interface was used for performing the exploratory analysis and to estimate the correlation among the studied items.

## **Results**

Energy and water consumption analysis is part of the research being performed on Energetic Efficiency and Sustainability at São Bento do Sul healthcare units. It was possible to establish that the climate is directly linked to energy consumption in buildings, as a result from this analysis, justifying the usage of solutions for improved efficiency in buildings, thereby aiding thermal comfort in period of extreme temperature variation.

An exploratory analysis was performed on electric and water consumption data from 16 healthcare units. Table 1 shows the obtained results from performing the exploratory analysis on the descriptive measurements on energy consumption.

Table 1 – Energy consumption descriptive statistics, PMSBS (2016).

	Minimum	1 <sup>st</sup> Quartile	Median	Average	3 <sup>rd</sup> Quartile	Maximum	Standard Deviation
2013	4877	8128	9007	9872	11400	14980	3092.351
2014	4710	9076	9926	10120	11030	14830	2469.538
2015	5155	9313	10100	10080	10860	13650	2101.806
2016	5488	10430	12880	13100	16180	18340	4338.058

Figure 1 display the monthly energy consumption from 2013 to 2016. The greatest electric energy consumption has proven to be during the coldest months, from June to September, adhering to the Bioclimatic Zone 1 characteristic, where the city of São Bento do Sul is located. Therefore, this increase in energetic consumption is due to heater usage during these periods. The consumption also decreased in January as the healthcare units were closed or operating partially.

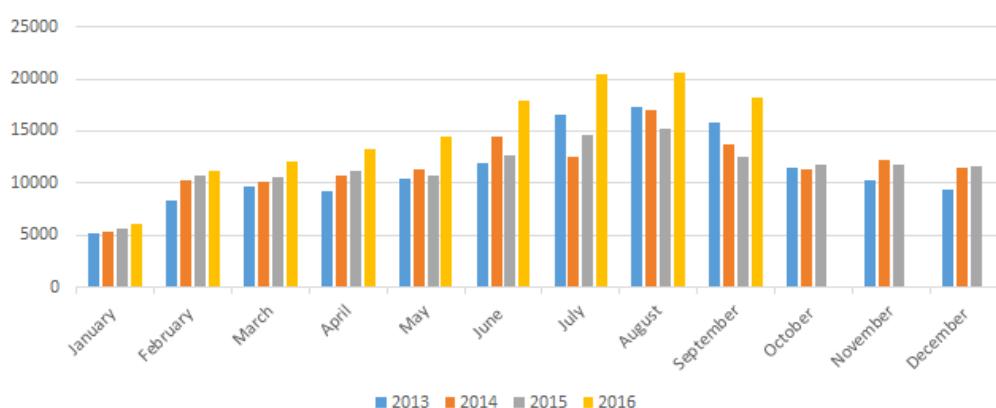


Figure 1 – Energy Consumption Graph on monthly comparison for 2013, 2014, 2015, and 2016 – Healthcare Units in São Bento do Sul – SC, (PMSBS, 2016).

Boxplots are displayed in Figure 2 on the energy consumption from these specific years, as increased energy consumption was verified throughout all months in 2016, due to the supply and installation of such equipment as computers, split air conditioners (hot and cold air), heaters, fans, according to information from the municipal Health Secretariat.

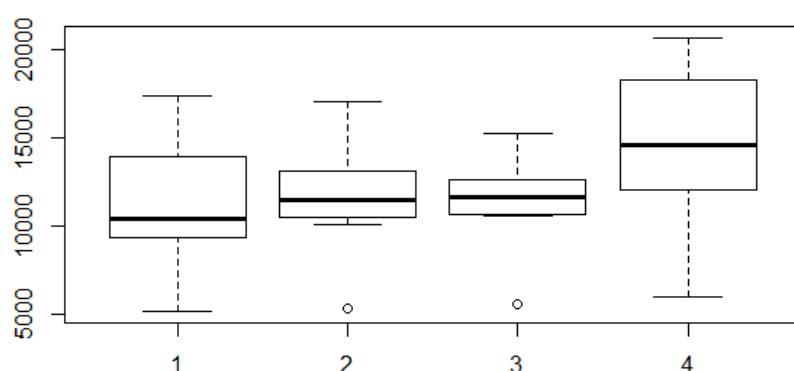


Figure 2 – Energy Consumption Boxplot Graph from 2013 (1), 2014 (2), 2015 (3), and 2016 (4) – Healthcare Units in São Bento do Sul – SC, (PMSBS, 2016).

There are possible outliers present, as displayed in Figure 2, in 2014 and 2015, as two cases occurred in January, whereas the decreased consumption values were 4710KWh and 5155KWh, respectively. These values are comparably much lower than other consumption values from those years, but when we compare the January values to other years, they are quite near the minimum values encountered for this month, which is justifiable, as it considers a period when there is no healthcare service provided in the units or just partially.

Greater monthly consumption values were reported in 2013 and 2016, supposedly due to greater temperature variation in seasons, justifying a future research study related to variable energy consumption based on temperature.

Exploratory analysis was performed on water consumption data obtained from the results displayed on table 2. The values used are derived from the measured consumption.  $10m^3$  is used as the minimum consumption fee in the city. However, the actual consumption values from each unit were used for the preparation of this research study, thereby obtaining more realistic analyses on consumption and possible leaks.

Table 2 – Water consumption descriptive statistics, PMSBS (2016).

	Minimum	1st Quartile	Median	Average	3 <sup>rd</sup> Quartile	Maximum	Standard Deviation
2013	186	209.8	217	224	232.5	280	28.59752
2014	144	182	202.5	201.6	215.5	285	36.54501
2015	80	137.8	156	150.4	169	177	26.50029
2016	71	150	178	186.9	207	343	73.06067

It is possible to confirm, according to the results shown in figure 3, there was increased consumption in the first months that can be characterized as leaks, even at a lesser degree. This hypothesis is justified, as activities during this period are fewer than the rest of the year, and, in the period when activities returned to normal, the water consumption decreased, adhering to that pattern until the end of the year.

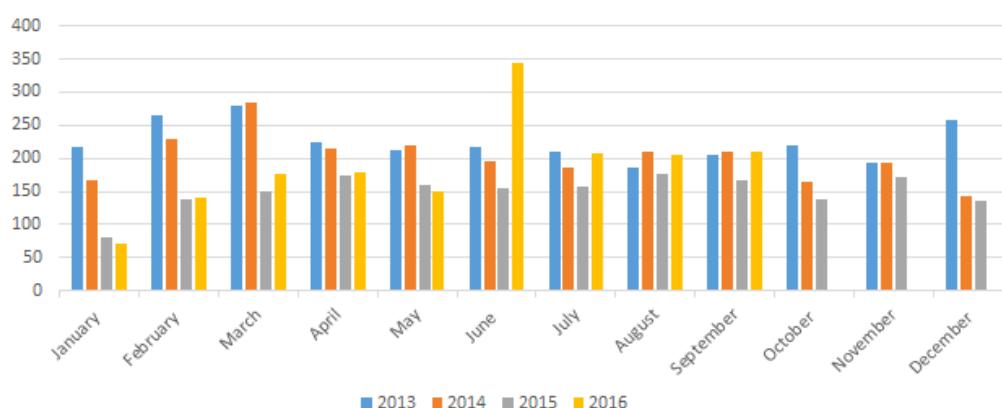


Figure 3 – Water Consumption Graph on monthly comparison for 2013, 2014, 2015 e 2016 – Healthcare Units in São Bento do Sul – SC, (PMSBS, 2016).

Yet in 2016 in the 6<sup>th</sup> month, a sudden peak in water consumption was noticed; possibly due to leakage, which was solved after the confirmation.

The water consumption, in the first month, was reduced throughout all analyzed years based on the following expressed data, displayed an increase beginning in the 2<sup>nd</sup> and 3<sup>rd</sup>

month, which can be characterized due to returning to supplying complete healthcare in units. Some locations observed a higher degree of consumption compared to other months. The Administration, through the Internal Control Sector, after observing consumption deviations, informed the Health Secretariat for verification of possible leaks in units.

A possible decrease in water consumption from 2013 to 2015 and a possible increase in 2016 were also established, as shown in figure 4, presumably corresponding to leaks.

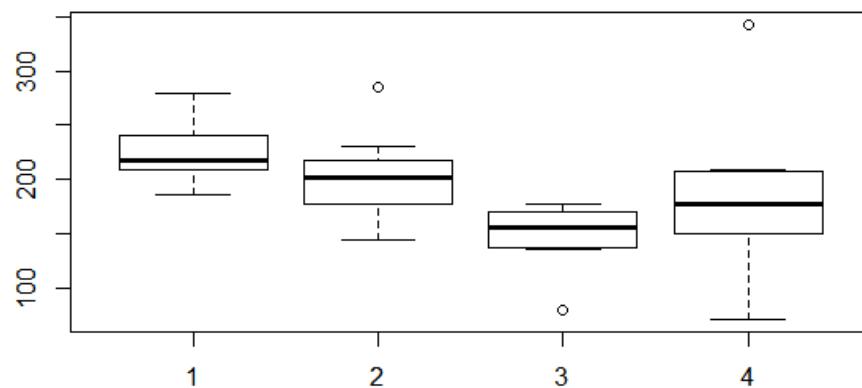


Figure 4 – Water Consumption Boxplot Graph from 2013 (1), 2014 (2), 2015 (3), and 2016 (4) – Healthcare Units in São Bento do Sul – SC, (PMSBS, 2016).

Following that, a correlation analysis was performed for studying the interrelationship among variables, as the correlation coefficient was expressed as 0.2292326 (p-value 0.1298) between the energy and water usage, whereas the classification was not relevant and did not display any interdependence among the items.

During certain cold periods of the year, there is increased energy usage as previously made explicit. This increase is related to using equipment for providing increased thermal comfort in winter. In order to decrease that, strategies must be employed in the building, seeking to enhance thermal comfort in buildings in wintertime, as to avoid excessive heater usage.

There are lower values for water, as well as energy consumption, in January, compared to other months of the year. However, water consumption remains similar during the other months, and, when there are high consumption peaks, it is necessary to assume there is some temporary problem, since afterwards; the normalization of the consumption pattern takes place.

Thus, aspects related to bio-climatic architecture, building supplies, equipment, and constructive technologies allowing better energy usage, must be adopted in the design planning phase, so there is no need to relinquish user comfort and make extreme use of resources.

According to Ballarini et al (2014), most residential buildings in the Piemonte region – Italy were built before 1976, and this factor made these basic renovations provide a significant increase in energetic performance. Furthermore, about 40% of energy can be saved by implementing a remodelling standard, according to the authors. As the Healthcare Units in São Bento do Sul still operate in old-fashion structures and characteristics, thus high rates of savings can also be achieved when a standard is properly studied for this region.

The results obtained from this initial data analysis will be afterwards used and aligned to cluster analysis for the obtainment of a model proposal to be used for sustainability analysis and energetic efficiency for these types of buildings in the city of São Bento do Sul -

SC. Cluster analyses have been used for investigating the potential for energy savings in buildings and the proposal of classifying buildings based on their energetic efficiency (Schaefer and Ghisi, 2016).

## Conclusions

The purpose of this article has been to evaluate electric energy and water consumption in the Healthcare Units in the city of São Bento do Sul using the data supplied by PMSBS, as well as verifying if there is any interrelationship among these variables.

It was possible to establish a relationship in energy consumption, in colder periods, as the consumption increased, clearly showing that energetic expense is linked to the local climate. There was an increase in energy consumption in 2016, justified by the purchase and installation of heating equipment. There is a certain degree of regularity in water consumption usage. The month of January is different from other months of the year, due to the complete or partial closing of units. Months with distorted consumption were possibly characterized as leaks. No connection was established between energy and water consumption.

An evaluation methodology for the energetic efficiency and sustainability will be applied to the São Bento do Sul healthcare units as continuity from this research study, employing the Eletrobrás RTQ-C labelling system (Quality Technical Regulation for Energetic Efficiency in Commercial, Service, and Public Buildings). There are bonuses granted in the RTQ-C system in the evaluation of a building operating energy and water saving equipment. The concepts of sustainability and energetic efficiency will also be verified in the São Bento do Sul municipal healthcare units, by using cluster analysis as a tool. After these analyses are performed, solutions will be proposed for improving sustainability and energetic efficiency in the São Bento do Sul Healthcare Units.

The results obtained from this study can aid municipal administrators in decision-making regarding initiatives and project planning seeking sustainability and energetic efficiency, thereby generating savings in public resources.

## References

- ABNT, Associação Brasileira de Normas Técnicas. (2005), *NBR 15220-3:2005 – Desempenho térmico de edificações – Parte 3: Zoneamento bioclimático brasileiro e diretrizes construtivas para habitações unifamiliares de interesse social*. Rio de Janeiro: ABNT.
- Ballarini, I., Corgnati, S. Paolo and Corrado, V. (2014). *Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project*. Energy Policy, 68 (pp. 273-284). Available at: [www.sciencedirect.com/science/article/pii/S030142151400032](http://www.sciencedirect.com/science/article/pii/S030142151400032) (accessed 09 March 2017).
- Brasil (2011). *Manual de Instruções para Projetos de Eficiência Energética nos Prédios Públicos - Utilização dos Recursos da Reserva Global de Reversão – RGR*. Rio de Janeiro: PROCEL-EPP. Available at: [www.eletrobras.com/elb/procel/main.asp?TeamID=%7B60F8B9E9-77F5-4C5B-9E94-B1CC0CEF1EAB%7D](http://www.eletrobras.com/elb/procel/main.asp?TeamID=%7B60F8B9E9-77F5-4C5B-9E94-B1CC0CEF1EAB%7D) (accessed 15 September 2016).
- Brasil (2010). Ministério do Desenvolvimento, Indústria e Comércio Exterior. Instituto Nacional de Metrologia, Normalização e Qualidade Industrial. *Portaria INMETRO nº 372: aprova o Regulamento Técnico da Qualidade para Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos*. 17 September 2010, Rio de Janeiro: INMETRO. Available at: [www.inmetro.gov.br/legislacao/detalhe.asp?seq\\_classe=1&seq\\_ato=1462](http://www.inmetro.gov.br/legislacao/detalhe.asp?seq_classe=1&seq_ato=1462) (accessed 5 September 2016).
- Chen, S. Q. and Chen B. (2016). *Urban energy–water nexus: a network perspective*. Applied Energy, 184 (pp. 905-914). Available at: [www.sciencedirect.com/science/article/pii/S0306261916303592](http://www.sciencedirect.com/science/article/pii/S0306261916303592) (accessed 28 February 2017).
- Gil, A. C. (1994). *Como elaborar projetos de pesquisa*. 3rd edition. São Paulo: Atlas.

Lamberts, R., Dutra, L. and Pereira, F. O. R (2014). *Eficiência energética na arquitetura*. 3rd edition. São Paulo: Eletrobras/Procel. Available at: [www.labeee.ufsc.br/sites/default/files/apostilas/eficiencia\\_energetica\\_na\\_arquitetura.pdf](http://www.labeee.ufsc.br/sites/default/files/apostilas/eficiencia_energetica_na_arquitetura.pdf) (accessed 15 May 2016).

Manfron, Vittorio et al (2006). *Costruire il Progetto Sostenibile*. Universidade IUAV de Veneza. Available at: [www.iuav.it/SISTEMA-DE/Archivio-d/approfondi/sostenibil/Saggio-bibliografico.pdf](http://www.iuav.it/SISTEMA-DE/Archivio-d/approfondi/sostenibil/Saggio-bibliografico.pdf) (accessed 15 May 2016).

Marinho, E. C. A. (2007). *Uso Racional da Água em Edificações Públicas*. Monografia. Universidade Federal de Minas Gerais. Available at: [www.cecc.eng.ufmg.br/trabalhos/pg1/USO%20RACIONAL%20DA%20C1GUA%20EM%20EDIFICA%C7%D5ES%20P%DABILICAS.pdf](http://www.cecc.eng.ufmg.br/trabalhos/pg1/USO%20RACIONAL%20DA%20C1GUA%20EM%20EDIFICA%C7%D5ES%20P%DABILICAS.pdf) (accessed 28 February 2017).

Menkes, M. (2004). *Eficiência Energética, Políticas Públicas e Sustentabilidade*. Doctoral Thesis. Universidade de Brasília. Available at: [www.iar.unicamp.br/lab/luz/Id/Arquitetural/efici%EAncia%20energ%E9tica/Pesquisa/eficiencia\\_energetica\\_politicas\\_publicas\\_e\\_sustentabilidade.pdf](http://www.iar.unicamp.br/lab/luz/Id/Arquitetural/efici%EAncia%20energ%E9tica/Pesquisa/eficiencia_energetica_politicas_publicas_e_sustentabilidade.pdf) (accessed 15 May 2016).

Ministério das Minas e Energia (2011). *Plano Nacional de Eficiência Energética: Capítulo 1*. Brasília: MME. Available at: [www.orcamentofederal.gov.br/projeto-esplanada-sustentavel/arquivos-peg/eficiencia\\_energetica\\_em-predios\\_publicos.pdf](http://www.orcamentofederal.gov.br/projeto-esplanada-sustentavel/arquivos-peg/eficiencia_energetica_em-predios_publicos.pdf) (accessed 18 May 2016).]

Ministério do Planejamento, Orçamento e Gestão (2014). Instrução Normativa nº 2. Dispõe sobre regras para aquisição de máquina e aparelhos consumidores de energia pela administração pública federal direta, autárquica e fundacional, e uso da etiqueta nacional de conservação de energia (ENCE) nos projetos e respectivas edificações federais nova ou que recebam retrofit. Available at: <http://www.comprasgovernamentais.gov.br/paginas/instrucoes-normativas/instrucao-normativa-no-2-de-4-de-junho-de-2014> (accessed 10 Nov 2016).

Prefeitura Municipal de São Bento do Sul (2016). *Tabelas com dados do consumo de energia elétrica e água das Unidades de Saúde do Município de São Bento do Sul*. São Bento do Sul: PMSBS.

Procelinfo (2017). Available at: <http://www.procelinfo.com.br/main.asp?Team=%7B505FF883-A273-4C47-A14E-0055586F97FC%7D> (accessed 30 May 2017).

R Core Team (2016). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Available at: [www.R-project.org](http://www.R-project.org) (accessed 28 February 2017).

Schaefer, A., and Ghisi, E. (2016). *Method for obtaining reference buildings*. Energy and Buildings, 128 (pp. 660-672). Available at: [www.sciencedirect.com/science/article/pii/S0378778816305977](http://www.sciencedirect.com/science/article/pii/S0378778816305977) (accessed 09 March 2017).

Silva, G. L. (2015). *Avaliação da eficiência energética em escolas públicas municipais e estaduais de Maceió – Alagoas*. Dissertation. Universidade Federal da Paraíba. Available at: <http://tede.biblioteca.ufpb.br/bitstream/tede/8386/2/arquivo%20total.pdf> (accessed 15 May 2016).

Vieira, A. S. and Ghisi, E. (2016). *Water-energy nexus in low-income houses in Brazil: the influence of integrated on-site water and sewage management strategies on the energy consumption of water and sewerage services*. Journal of Cleaner Production, 133 (pp. 145-162). Available at: [www.sciencedirect.com/science/article/pii/S0959652616305765](http://www.sciencedirect.com/science/article/pii/S0959652616305765) (accessed 28 February 2017).

Zhang, X. and Vesselinov, V. (2016). *Energy-water nexus: balancing the tradeoffs between two-level decision makers*. Applied Energy, 183 (pp. 77-87). Available at: [www.sciencedirect.com/science/article/pii/S030626191631265X](http://www.sciencedirect.com/science/article/pii/S030626191631265X). (accessed 28 February 2017).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Can thermal perception in a building be predicted by the perceived spatial openness of a building in a hot and humid climate?

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**Abstract:** The authors wanted to prove that there is a large correlation between the concepts spatial openness and comfort (visual, wind speed and thermal) perception in people's minds in a hot and humid climate in summer in order to be able to use spatial configuration parameters such as openness, connectivity and depth as a design tool for a comfortable and energy efficient building in the early design stages. 513 local Chinese college architecture students in 2015 were questioned about the relationship between spatial openness and comfort perception. The main findings for a hot and humid climate are: a. spatial openness of a particular space significantly effects occupants' visual perception, wind speed perception and thermal perception in a particular space ( $p < .05$ ). b. There is a strong effect size between spatial openness and visual and wind perception ( $\omega = .50$  and  $.54$ ); the effect size of the thermal perception is weaker ( $\omega = .14$ ). c. The comfort perception is strongly influenced by the time of day, therefore visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort.

**Keywords:** Spatial openness, thermal environmental perception, adaptive thermal comfort

### Introduction

Architecture as a shelter protects people from the natural environment through various architectural elements: floors, walls, columns, windows, doors and roofs. These elements can be identified as architectural boundaries, which distinguish the outdoor from the indoor environment and the various indoor spaces from each other. The outdoor and indoor architectural boundaries determine a spatial environment. In a particular spatial environment, next to the basic functional requirements for occupants' activities, the perceptions of the occupants such as aesthetics, delight and comfort, are also very important for the quality of a built environment. Studying the relationship between the spatial environment and the way the spatial environment is perceived can yield important insights into the way architectural design can create more comfortable living environments.

Comfort (especially thermal comfort) is heavily related to building energy consumption; therefore comfort is one of the most important considerations in modern architectural design within the scope of sustainable development. A wealth of thermal environment studies have investigated the relationship between building shape, geometry and envelop, and thermal environment (Yi and Malkawi, 2009, Hirano et al., 2006, AlAnzi et al., 2009, Ratti et al., 2003, Naraghi and Harant, 2013), yet less research has been carried out on the influence of the spatial configuration, i.e. the relative arrangement of parts or elements in a three-dimensional space, inside a building on the thermal environment and occupants' thermal perception.

Common sense tells us that in summer in a hot and humid climate there is a correlation between the concepts spatial openness and comfort perception in people's minds. The authors' hypothesis is that there is a large correlation between the concepts spatial openness and comfort perception in people's minds. If this hypothesis is true, using spatial configuration is a good design tool for (thermal) comfort in the early design stages.

This hypothesis is tested by questioning around 500 Chinese architecture students about their comfort perception in several spatial environments in summer in a hot and humid climate. Five different spatial environments with different spatial openness were described in writing as indoor space, semi-outdoor space, outdoor space, a room with a large operable area and a room with a small operable area. The three perceptions were visual perception, thermal perception and wind perception. The comfort perception over the day for the different spatial environments was also investigated. A similar questionnaire was given to Dutch architecture students, but the results were inconclusive due to the low number of responses.

### **Study method**

In 2015, a written questionnaire was administered to 513 Chongqing University bachelor students of architecture during one of their courses within one week. It was estimated that the questionnaire would take about 10 minutes to complete. The filled out questionnaire had to be handed in when the class was finished.

The written questionnaire was obligatory, anonymous and in Chinese and English. The questionnaire was developed by one of the authors. The questionnaire included 10 questions of four parts. The first part consisted of questions requesting demographic information, such as gender (male, female) and age (between 17 and 25 years old or not). The second part included questions relating to the general perception of the local climate in summer. This included thermal sensation (slightly cool, neutral, slightly warm, warm and hot), air velocity preference (not noticeable air velocity, low air velocity, high air velocity and very high air velocity) and preferred changes to the student's living room (air movement, operable window size, openness of the living room, presence of balcony or terrace, presence of courtyard or patio). The questions in the third part were related to the visual perception (good, neutral, not so good), wind speed perception (too low, low, neutral, high, too high) and thermal perception (cold, cool, neutral, warm, hot) in the different types of spatial environments: indoor space (a space with small openings), semi-outdoor space (a space with large openings), and outdoor space. The fourth part included questions about occupants' spatial preferences for different spatial environments (indoor space, semi-outdoor space, outdoor space, no preference) at different times (morning, afternoon, evening, and night). The last questions were about the preferred view from the room (good view or no preference and broad or narrow view). It should be noted, the students were obliged to fill in the questionnaire. This led to some students not answering the questions fully or not answering the questions seriously. All data was entered in Excel and SPS. All incomplete questionnaires were deleted. Descriptive statistics such as percentages, range (minimum and maximum), or arithmetic mean with standard deviation (SD) were used to summarize the characteristic of the students and their homes.

## Results

### ***General perception of the local climate***

The subjects were 62% male and 38% female, aged between 17-25. Figure 1 shows the general thermal perception and wind speed perception in summer. It was found that 50% of the subjects felt very hot and 60% indicated that the wind speed perception was low under local climate conditions. That means that thermal perception and wind speed perception are negatively perceived and that the local occupants are not satisfied with the thermal environment.

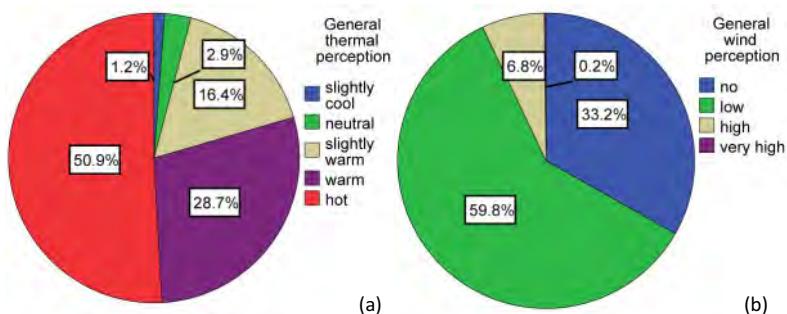


Figure 1. General thermal and wind speed perception of the local climate (Chongqing, China, 2015) by 513 local college students of architecture.

### ***The correlation of spatial openness and subjects' perception***

Figure 2 shows the visual perception, wind speed perception and thermal perception according to the spatial openness. It is found that the visual perception increases from small opening to indoor space to semi-indoor space to big opening to outdoor space, thus from an enclosed space to an open space, which means the subjects think they can obtain a broader and better view in the more open spaces than in the enclosed spaces. The one-sided ANOVA analysis showed that there was a significant effect of the spatial openness on the view,  $F(4, 2543) = 266$ ,  $p < 0.01$ ,  $\omega = .54$ . Planned contrasts revealed that more spatial openness significantly increased the view, see figure 2(a).

The subjects feel they can catch more wind in the more open spaces than in the enclosed spaces, see figure 2(b). Performing a one-way independent ANOVA statistical analysis, the variants are significantly different ( $p < 0.01$ ) according to Levene's test of homogeneity of variances. Therefore the Brown-Forsythe robust test of equality of means is used. This test indicates a significant effect of the spatial openness on the wind speed perception,  $F(4, 2485) = 213$ ,  $p < .01$ ,  $\omega = .50$ . Planned contrasts revealed that wind speed perception is significantly lower in the indoor environment compared to the small opening environment,  $t(735) = 13.6$ ,  $p < 0.01$  (1-tailed),  $r = .44$ ; wind speed perception is significantly higher in the semi-outdoor environments compared to the indoor environment,  $t(713) = 17.8$ ,  $p < 0.01$ ,  $r = .55$ ; wind speed perception is significantly higher in the large opening environment compared to the semi-outdoor environment,  $t(994) = 4.9$ ,  $p < 0.01$ ,  $r = .15$ ; wind speed perception is significantly lower in the outdoor environment compared to the big opening environment( $950) = 1.75$ ,  $p < 0.05$ ,  $r = .06$ .

A significant effect between spatial openness and thermal comfort is also expected for thermal perception from figure 2(c), with the exception of the outdoor environment which is perceived to be the hottest of all spatial environments. Performing a one-way independent ANOVA statistical analysis, the variants are significantly different ( $p < 0.05$ ) according to Levene's test of homogeneity of variances. Therefore the Brown-Forsythe

robust test of equality of means is used. This test indicates a significant effect of the spatial openness on the thermal perception,  $F(4, 2553) = 13.7$ ,  $p < .01$ ,  $\omega = .14$ . Planned contrasts revealed that thermal perception is significantly hotter in the indoor environment compared to the small openings environments,  $t(1016) = 1.82$ ,  $p < 0.05$  (1-tailed),  $r = .06$ ; thermal perception is significantly hotter in the semi-outdoor environments compared to the indoor environment,  $t(1000) = 3.32$ ,  $p < 0.01$ ,  $r = .10$ ; thermal perception is significantly hotter in the large opening environment compared to the semi-outdoor environment,  $t(934) = 1.7$ ,  $p < 0.05$ ,  $r = .06$ . There was no significant effect between the thermal perception of the outdoor environment and the small opening environment. The effect sizes are smaller than expected. This is probably caused by the fact that more than 40 % of the students consider all spatial environments warm or hot.

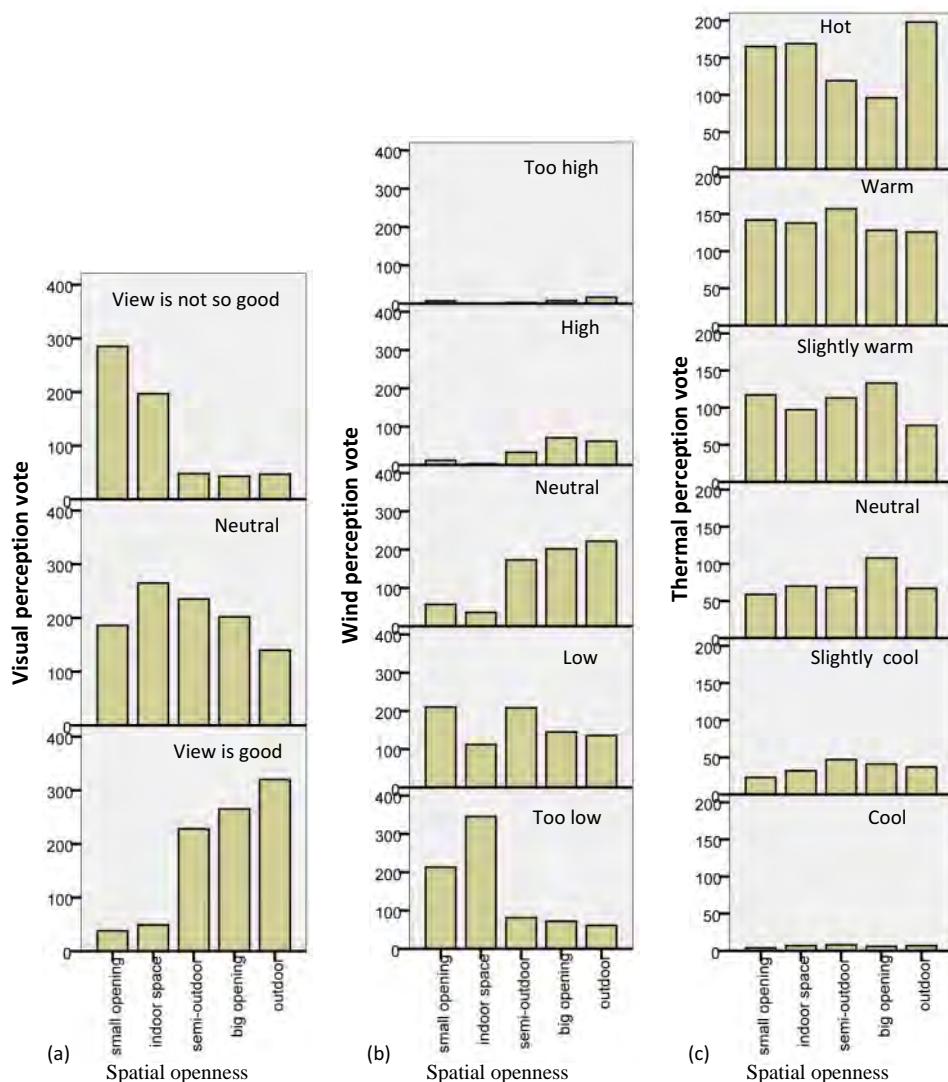


Figure 2. Visual perception, wind speed perception and thermal perception according to spatial openness in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture.

A significant effect between visual perception, wind speed perception and thermal perception has been found from a one-way independent ANOVA statistical analysis for the three perception pairs, as shown in table 1. The variants are significantly different for all three pairs ( $p < 0.01$ ) therefore the Brown-Forsythe robust test of equality of means is used to determine if there is a significant effect between thermal, wind speed and visual perception.

The correlation between visual perception and wind speed perception is the strongest  $\omega = .39$ . The correlation coefficient between thermal perception and wind speed perception is  $\omega = 0.31$ . The correlation between visual perception and thermal perception is relatively weak  $\omega = .20$ .

Table 1 Statistical results of the correlation between visual perception, wind speed perception and thermal perception in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture.

(a)		Wind perception(%)					
		too low	low	neutral	high	too high	Total
Visual perception	good	13.5	30.1	41.3	13.1	2.0	100
	neutral	32.3	35.6	26.2	5.2	0.6	100
	not so good	55.1	30.3	10.6	2.2	1.8	100
Total		31.1	32.4	27.8	7.3	1.4	100
$\omega=0.39, p < 0.01, F(4,240) = 102$							

(b)		Thermal perception( %)						
		cool	slight cool	neutral	slight warm	warm	hot	Total
Visual perception	good	2.0	10.4	19.8	18.2	24.8	24.8	100
	neutral	0.7	6.3	13.7	25.5	28.2	25.5	100
	not so good	1.0	3.4	7.9	17.6	28.8	41.4	100
Total		1.2	7.1	14.5	21.0	27.1	29.1	100
$\omega=0.20, p < 0.01, F(4,484) = 21$								

(c)		Wind perception( %)					
		too low	low	neutral	high	too high	Total
Thermal perception	cool	36.7	16.7	23.3	23.3	0.0	100
	slight cool	14.0	25.3	33.7	23.6	3.4	100
	neutral	14.8	29.0	45.4	9.2	1.7	100
	slight warm	23.7	38.2	31.9	5.5	0.8	100
	warm	28.7	39.7	24.4	6.5	0.6	100
	hot	50.5	26.1	17.8	3.4	2.2	100
Total		31.0	32.6	27.7	7.2	1.4	100
$\omega=0.31, p < 0.01, F(4, 483) = 50$							

On the basis of the questionnaire results described above, it is found that visual perception and wind speed perception and thermal perception are significantly different in different spatial environments. In general, a more open space is perceived as having a better view, a higher wind speed and a lower temperature. There are a few exceptions. The most open space, outdoor space, is perceived the hottest, probably because the solar radiation in open spaces, such as the outdoor space is stronger than in the indoor spaces. The indoor space is perceived to have a lower wind speed than the more enclosed small opening environment, probably because the description "indoor space" gives too little information about the window openings and students can have imagined closed windows. The outdoor space is not perceived as having a larger wind speed than the large opening

environment. This is probably caused by the different activities in the outdoor space and the fact that when there is sun, a larger wind speed is necessary to feel comfortable.

### **Spatial preference**

Figure 3 shows the subjects' general spatial preference in summer. It can be seen that more than 90% of the subjects prefer an environment with a good and broad view, and with considerable natural ventilation. The subjects' spatial preference with respect to the time of day is shown in figure 4. In the morning, the subjects show little spatial preference for the indoor space, semi-outdoor space or the outdoor space. This can be explained by the fact that the temperature differences between the different spatial environments are relatively small in the morning in the local summer climate. Hence, spatial preference is not strongly determined by the thermal environment, with other factors, such as activities, largely influencing the spatial choice. In the afternoon, half of the subjects prefer to stay in the indoor space, the second preference is the semi-outdoor space and the third preference is the outdoor space. This is probably due to the fact that the subjects know from experience that during the afternoon, as the outdoor temperature rises, the solar radiation in the outdoor and semi-outdoor space is stronger than in the indoor space. In the evening, more than 60% of the subjects prefer to stay in the semi-outdoor and outdoor space. This is probably because the indoor temperature is higher than the temperature in the outdoor or semi-outdoor space in the evening. Moreover, the subjects prefer to stay outside to catch more natural ventilation. At night, almost 40% of the subjects prefer the indoor spaces; however, some 45% of the subjects still prefer to stay in the semi-outdoor or outdoor space. This is probably because the heat in the indoor space is not easily dissipated at night, so that the indoor temperature is still high while the outside temperature has already dropped. The choice of activity is assumed to be the reason for the subjects to withdraw to the indoor space, although in terms of the thermal environment, subjects prefer to stay outside. An investigation by Fu (2002) in the studied region, showed that 60 to 90% of the local inhabitants complained that they were sleepless at night during summer due to the sweltering and sultry weather.

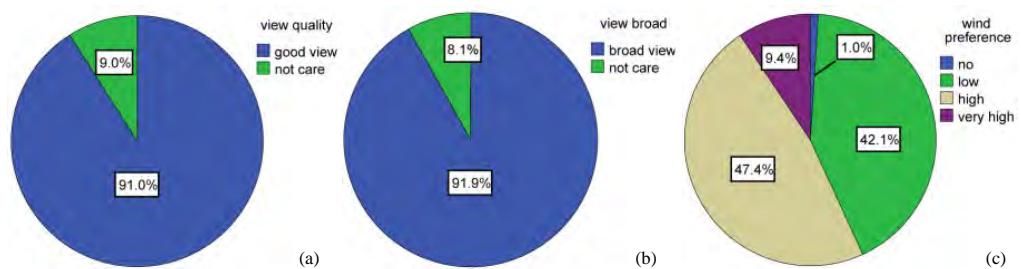


Figure 3 Subjects' general spatial preference in summer in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

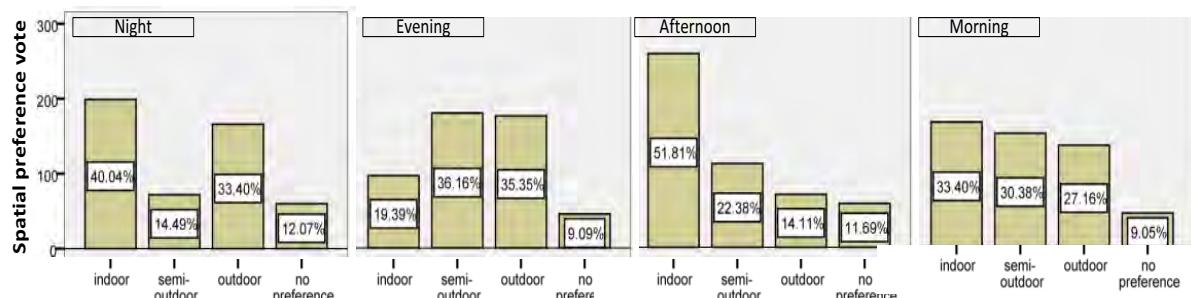


Figure 4 Subjects' spatial preference respect to the time of day in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

## Discussion

The questionnaire showed that, under hot and humid climate conditions, spatial openness features, occupants' visual perception, wind speed perception and thermal perception are all associated. The strongest correlation is between spatial openness and visual perception and wind speed perception. The correlation between wind speed perception and thermal perception is considerable as well. It may be inferred that if a certain space offers good openness, occupants are likely to have a positive visual and wind speed perception, and even thermal perception. In fact, wind speed perception is the key factor in the chain, see figure 5.

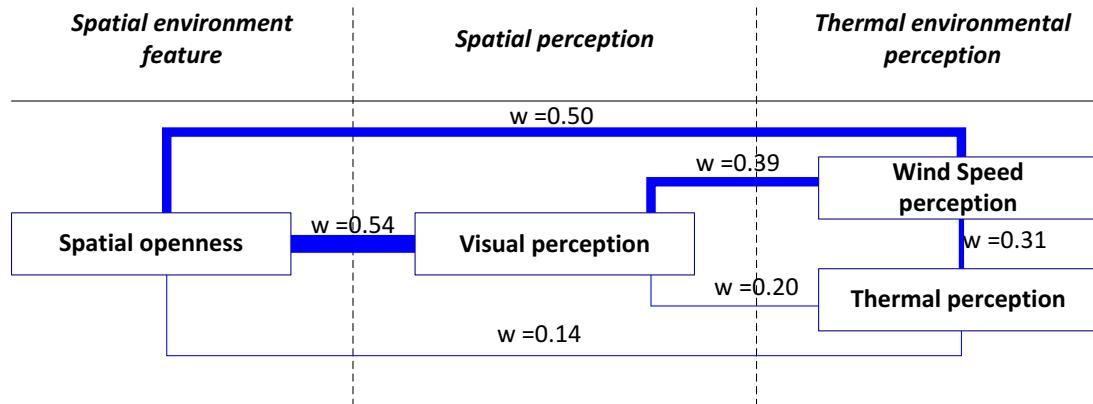


Figure 5 The effect sizes between spatial openness, spatial perception and thermal environmental perceptions in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

A lower effect size between spatial openness and thermal perception is found than was expected. This is probably caused by the fact that more than 40 % of the students consider all spatial environments warm or hot causing the variants to be were significantly different ( $p < 0.01$ ) according to Levene's test of homogeneity of variances. The different comfort perceptions did not have the same order of preferences. The outside environment was the best visual perception, but the worst thermal perception and an average wind perception. Future research should be more specific on the description of the spatial environments if the expected high correlation between spatial openness and the comfort perceptions is to be found.

Occupants' spatial preference or movement in the domestic building is influenced by their perception with respect to the time of day. This can, besides the high amount of warm and hot votes, also explain the low effect size between spatial openness and thermal perception. The questionnaire did not ask this explicitly, but the opinion of the authors is that a large part of the spatial preference over the day is temperature dependent. This means that the time of day also influences the relationship between the spatial openness and the thermal perception.

The questionnaire proves that spatial boundary conditions can strongly influence occupants' comfort perception, and subsequently influence occupants' spatial choice and movement in a particular thermal environment, given the opportunity, as Humphreys (1997) pointed out: when people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like.

## Conclusion

In this paper, local architectural students' spatial perception and comfort perception were investigated through a questionnaire. The main findings for a hot and humid climate are: a.

Spatial openness of a particular space significantly effects occupants' visual perception, wind speed perception and thermal perception in a particular space. b. There is a strong effect size between spatial openness and visual and wind perception ( $\omega = .50$  and  $.54$ ); the effect size of the thermal perception is weaker ( $\omega = .14$ ). c. The comfort perception is strongly influenced by the time of day, therefore visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort theory.

The authors' hypothesis that there is a large correlation between the concepts spatial openness and comfort perception in people's minds has not been proven. The effect size between spatial openness and thermal perception is too low. However, the effect size between spatial openness and visual and wind speed perception is high, as expected. The low effect size is probably caused by a too large amount of warm and hot votes (< 40%) for all spatial environments, the fact that solar irradiation unconsciously influences the perceived temperature in the outdoor environment and the fact that the preferred spatial environment is shown to change over the day. The authors, therefore, do not yet reject their hypothesis that spatial perception and comfort perception are highly correlated. More research, such as a more advanced questionnaire, is, therefore, needed for further proof.

As already mentioned, spatial openness significantly effects comfort perception for architectural students in a hot and humid climate. This means that architectural students in a hot and humid climate can distinguish the effects of spatial openness on the comfort perception. This fact can be used in the education in the early design stages for buildings in a hot and humid climate. This is important because significant mistakes in spatial design in the early design stages are difficult to adjust later.

## References

- ALANZI, A., SEO, D. & KRARTI, M. 2009. Impact of building shape on thermal performance of office buildings in Kuwait. *Energy Conversion and Management*, 50, 822-828.
- FU, X. 2002. Building energy saving technology in hot summer and cold winter region, Beijing, China Architecture and Building Press.
- HIRANO, T., KATO, S., MURAKAMI, S., IKAGA, T. & SHIRAIISHI, Y. 2006. A study on a porous residential building model in hot and humid regions: Part 1—the natural ventilation performance and the cooling load reduction effect of the building model. *Building and Environment*, 41, 21-32.
- HUMPHREYS, M. A. 1997. An adaptive approach to thermal comfort criteria. In: CLEMENTS CROOME, D. (ed.) *Naturally Ventilated Buildings: Building for the Senses, the Economy and Society*. London E and FN Spon.
- NARAGHI, M. H. & HARANT, A. 2013. Configuration of Building Facade Surface for Seasonal Selectiveness of Solar Irradiation-Absorption and Reflection. *Journal of Solar Energy Engineering-Transactions of the Asme*, 135.
- RATTI, C., RAYDAN, D. & STEEMERS, K. 2003. Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and Buildings*, 35, 49-59.
- YI, Y. K. & MALKAWI, A. M. 2009. Optimizing building form for energy performance based on hierarchical geometry relation. *Automation in Construction*, 18, 825-833.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Airflow pattern and thermal comfort in winter by different combinations of air distribution strategies and window types in an office unit

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**Abstract:** Achieving favourable indoor comfort is a major concern in architectural design process. Different locations of air supply registers produce different airflow patterns, which cause spatial variations in indoor air temperature and thermal comfort. This paper studied a model private office with a variety of vent locations and window properties. The resulting spatial variations in indoor air temperature and thermal comfort and the related heat transfer through windows were compared. Autodesk® CFD was utilized to model the office space and air conditioning system, as well simulate the airflow in the indoor space. It is found that placing air supply vents under exterior windows effectively achieved uniform air temperature distribution and thermal comfort conditions when low-insulation windows were in use, even though such placement caused more heat losses through those windows. However, in a high-insulation window scenario, the air supply vent locations had only a minor effect on spatial variations in vertical temperature and thermal comfort, and a significant impact on heat loss through the windows. The findings offer insight into thermal comfort and energy issues as they are affected by vent location and building window type. This work also suggests possible ways of optimizing air vent placement and building window design.

**Keywords:** Thermal comfort, office, spatial variation, vent location, window properties

### Introduction

Maintaining thermal comfort is one of the most important aims of architectural design (Azizpour et al. 2013). Studies have demonstrated the strong correlation between indoor thermal comfort and user wellbeing, productivity, and health (Wagner et al. 2007; Azizpour et al. 2013). One way of achieving a desirable balance between thermal comfort and energy savings is by controlling the Heating Ventilation and Air Conditioning (HVAC) system (Ferreira et al. 2012).

In order to understand the HVAC system impacts on thermal comfort, a number of thermal comfort models have been proposed (Cheng et al. 2012). The most widely used is the Fanger model, which solves the heat balance equations between the human body and its surroundings environmental parameters (Fanger 1972). This model is included in the most frequently cited thermal comfort standards: ASHRAE 55-2013 (Standard 2013) and ISO 7730 (Standard 1994). Six variables are normally used to predict a subjective thermal comfort level, including: dry bulb air temperature, mean radiant temperature, air velocity, air humidity level, clothing worn on the body, and the activity level of the inhabitant (ASHRAE 2013). However,

in an actual interior environment, these six variables are normally dynamic, responding to under various situations of building envelope, exterior weather, interior system operation, and user behaviour, thus affecting the thermal comfort level.

In this work, two of these elements were of particular interest: exterior building windows and air vents. A building's exterior windows play an important role in maintaining indoor thermal comfort and energy consumption, since they usually make up a relatively large portion of the building envelope and often are less thermally insulating than the envelope's opaque components. In individual enclosed offices, providing an appropriate supply diffuser and return grille will ensure satisfactory air circulation (Grondzik & Kwok 2014; Janis & Tao 2013). Accordingly, one of the most common design concerns related to thermal comfort is the placement of air vents.

These two elements are often correlated. For instance, in winter, cool air from with exterior windows makes the air flow across the floor such that occupants may feel uncomfortable. In particular, during the winter season, the injection into the room of warm room air from the heating system causes cooler air to sink. This movement of cool air may create cold drafts near the floor, leading to thermal discomfort. Hence, the placement of forced-air registers has conventionally been underneath exterior windows, in order to force the warm air to rise and mix with cooler air. This has been demonstrated as an effective thermal comfort improvement solution (Carrier & Air 1965). Nevertheless, such placement may not only affect thermal comfort but also potentially impact thermal transfer between the interior and exterior. Locating air supply vents underneath exterior windows has historically been the practical answer, due to the conventional thermal property features of windows. It is well recognized that among a building envelope's elements, the windows' inner surface is normally the coldest part in winter and the hottest in summer. Vents placed underneath exterior windows may undesirably enhance heat transfer, due to the large contact area and high-speed air flows produced from vents. Consequently, this thermal transfer may result in a conflict between the goals of thermal comfort and energy savings.

Thanks to recent advancements in glass materials and fenestration technology, the thermal performance of windows has dramatically improved. More and more attention has been paid to designing and improving windows' thermal properties, while also maintaining the optical properties that govern daylight availability and view (Wang et al. 2016). It has been proposed that certain strategies, including the replacement of existing windows with high energy-performance substitutions and the introduction of shading devices and solar control glasses, would lower energy consumption and facilitate thermal comfort (Carletti et al. 2014). Researchers must now ask: with these newly developed and installed window products, is the conventional placement of vents under exterior windows still necessary to thermal comfort?

Studies have examined various aspects of this issue, especially about the balance between energy use and indoor thermal comfort (Azizpour et al. 2013; Nicol & Humphreys 2002). However, the role of vent location in indoor thermal comfort and energy performance continues to be under-researched. In the present study, we investigated the locations of air supply air registers and layouts of air grilles in a typical private office; we also considered if interactions with exterior windows influenced thermal comfort and heat transfer. The thermal comfort parameters considered included airflow pattern, temperature distribution, and predicted mean vote (PMV). Thermal transfer was accessed by investigating the heat flux in and out of the office room through any exterior window. For comparison, the thermal comfort level and heat transfer of two different vent placements were simulated in

Autodesk® CFD. The potential user comfort effects were indicated on an indoor thermal comfort map, revealing the spatial variations. The effects on the PMV index and heat flux through the exterior windows were analysed by comparing airflow patterns and air vent locations. The results of this research will shed light on the best design and placement of air vents for balancing energy efficiency and thermal comfort.

## Methodology

### Analytical procedure and method

This study used Autodesk® CFD to analyse the 3D turbulence flow and heat transfer inside a typical private office. The standard  $k - \varepsilon$  turbulence model was used to predict the turbulent airflow. Mass conservation and Navier-Stokes equations were solved, along with energy equations. A turbulence intensity of 5% and atmospheric pressure (0 Pa) were used as the vent inlet and the outlet boundary conditions, respectively. The above-mentioned simulation methods were used to obtain the PMV index of thermal comfort, temperature distribution inside the office, and heat transfer energy.

### Governing equations

The governing time-averaged fluid flow and heat transfer calculations are related to the continuity equation, Navier-Stokes equations, and thermal energy equation, which are shown in Eqs. (1) ~ (3).

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + v \frac{\partial \rho}{\partial y} + w \frac{\partial \rho}{\partial z} = 0 \quad (1)$$

where  $\rho$  is the density; and  $u$ ,  $v$ , and  $w$  are the  $x$ ,  $y$ , and  $z$  components of velocity, respectively.

$$\begin{cases} \rho \frac{\partial u}{\partial t} + \mu u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} = \rho g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left[ 2\mu \frac{\partial u}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + S_\omega + S_{DR} \\ \rho \frac{\partial v}{\partial t} + \mu u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} = \rho g_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ 2\mu \frac{\partial v}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \right] + S_\omega + S_{DR} \\ \rho \frac{\partial w}{\partial t} + \mu u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} = \rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ 2\mu \frac{\partial w}{\partial z} \right] + S_\omega + S_{DR} \end{cases} \quad (2)$$

The two source terms in the momentum equations,  $S_{DR}$  and  $S_\omega$ , were the rotating coordinates and distributed resistances, respectively. The distributed resistance term,  $S_{DR}$ , can generally be written as:

$$S_{DR} = - \left( K_i + \frac{f}{D_H} \right) \frac{\rho V_i^2}{2} - C \mu V_i \quad (3)$$

where  $i$  refers to the global coordinate direction ( $u$ ,  $v$ , and  $w$  in the momentum equation); and the  $K$ -factor can only operate on a single momentum equation at a time because each direction has its own unique  $K$  factor. The other two resistance types operate equally on each momentum equation.

The final source term was rotating flow. This term can generally be written as:

$$S_\omega = -2\rho \omega_i V_i - \rho \omega_i \times \omega_i \times r_i \quad (4)$$

where  $i$  refers to the global coordinate direction,  $\omega$  is the rotational speed, and  $r$  is the distance from the axis of rotation.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \frac{\partial T}{\partial x} + \rho C_p v \frac{\partial T}{\partial y} + \rho C_p w \frac{\partial T}{\partial z} = \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] + q_v \quad (5)$$

where  $C_p$  refers to the constant pressure-specific heat,  $k$  is the thermal conductivity,  $T$  is the temperature, and  $q_v$  is the volumetric heat source.

Heat transfer through an exterior window can be calculated from:

$$Q = q(T_{indoor} - T_{outdoor}) \quad (6)$$

where  $\varrho$  is the amount of heat transfer energy from the indoors to the outdoors through a window;  $q$  is the heat extraction rate, which is related to a window's overall thermal coefficient and area;  $T_{indoor}$  is the indoor temperature; and  $T_{outdoor}$  is the outdoor temperature.

### **Thermal comfort model in the simulation**

Based on the assumption of homogenous thermal conditions, The Fanger thermal comfort model was used to calculate the PMV, as seen in Eq. (7):

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M - W) - 3.96 \times 10^{-8}f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a) \\ - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) \\ - 0.0014M(34 - t_a)\} \quad (7)$$

where  $f_{cl}$  is the clothing factor  $f_{cl} = 1.0 + 0.2I_{cl}$  or  $1.05 + 0.1I_{cl}$ ;  $I_{cl}$  is the clothing insulation [clo];  $t_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\}$ ;  $R_{cl}$  is the thermal insulation from clothing,  $R_{cl} = 0.155I_{cl}$ ;  $M$  is the metabolic rate [ $W/m^2$ ];  $p_a$  is the vapor pressure of air [kPa];  $t_a$  is the air temperature [ $^\circ C$ ];  $t_{cl}$  is the surface temperature of the clothing [ $^\circ C$ ];  $t_r$  is the mean radiant temperature [ $^\circ C$ ];  $w$  is the external work;  $h_c$  is the convective heat transfer coefficient,  $h_c = 1.2(V)^{1/2}$ ; and  $V$  is the air velocity [m/s].

### **Numerical model and boundary conditions**

In this study, we used Cincinnati, OH as the location for external boundary conditions of the model. An actual interior image of the private office used in this simulation is shown in Fig. 1. The dimensions of the office were  $4.57m \times 3.05m \times 3.05m$  (clear length  $\times$  clear width  $\times$  clear height). The door's dimensions were  $2.18m \times 0.91m$  (height  $\times$  width). The window's dimensions were  $2.13m \times 2.99m$  (height  $\times$  width). The thickness of the wall was  $0.20m$ . The thicknesses of the ceiling and floor were both  $0.30m$ . The radius of the duct was  $0.15m$ , and the terminal dimensions were  $0.30m \times 0.30m$ . There were two lamps ( $1.22m \times 1.22m$  for each) installed in the ceiling. Regarding the thermal properties, the only thermal transfer boundary was set for the side with an exterior window; the other surfaces were set as adiabatic material. Table 1 shows the relevant thermal boundary conditions. The window insulation included two levels: low (L) and high (H). These represented the traditional single pane window system and contemporary triple-pane windows, respectively.



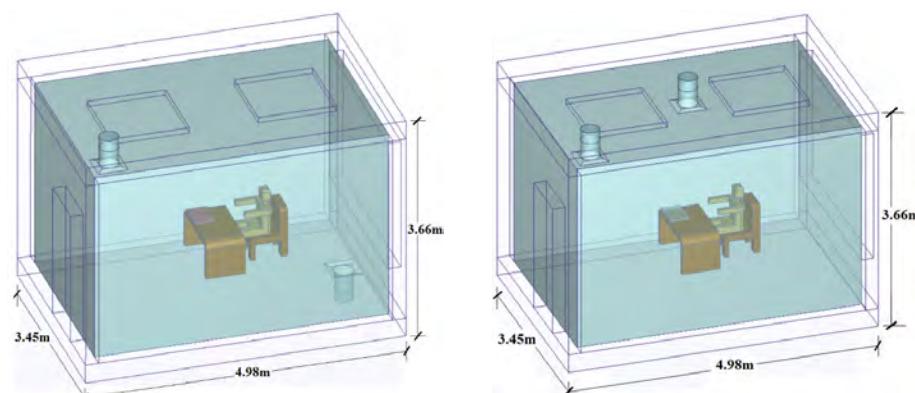
Figure 1. Interior of the case study office.

Two different vent locations were analysed. In Model 1, as shown in Figs. 2(a) and (c), the air supply vent was located on the floor underneath the exterior window, and the air return grille was positioned on the ceiling, near the door. In Model 2, as shown in Figs. 2 (b) and (d), the air supply vent was located near the centre of the ceiling, and the air return grille was placed in the same position as in Model 1. The air supply conditions were set at a volume flow rate of

$0.047\text{m}^3/\text{s}$  and an air temperature of  $25^\circ\text{C}$ . There were three heat sources in the office, including: 1) the metabolic heat power of one user, at  $60\text{W}$ ; 2) the dissipated heat power of one laptop, also at  $60\text{W}$ ; and 3) the dissipated heat power of the lamps, each at  $100\text{W}$ .

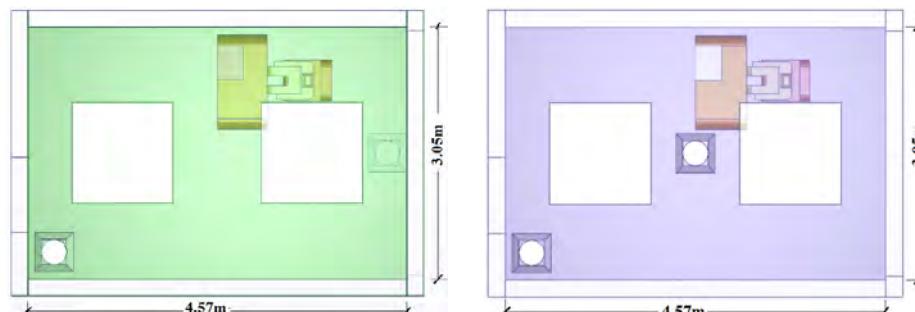
Table 1. Materials and Boundary Conditions of the CFD Model

Model	Window		Inlet		Outlet	External
	Construction	U-factor (W/m <sup>2</sup> -K)	Volume Flow Rate (m <sup>3</sup> /s)	Temperature (°C)	Pressure (Pa)	Temperature (°C)
1L	Single pane	5.6	0.047	25	0	0
1H	Triple pane	0.65	0.047	25	0	0
2L	Single pane	5.6	0.047	25	0	0
2H	Triple pane	0.65	0.047	25	0	0



(a) 3D view of Model 1

(b) 3D view of Model 2



(c) Top view of Model 1

(d) Top view of Model 2

Figure 2. Geometric views of the models with different vent layouts.

In addition, the following assumptions were made for the CFD simulation:

- 1) The airflow inside the office was stable;
- 2) The airflow met the Boussinesq approximation;
- 3) Thermal radiation was neglected;
- 4) The airflow inside the office was an incompressible Newtonian fluid;
- 5) The ceiling, floor, and three inner walls were perfectly adiabatic and did not transfer heat; and
- 6) The office obtained homogenous thermal conditions when the thermostat arrived at a thermally comfortable temperature.

## Results and discussion

Using the aforementioned approach, we formulated four combinations of vent locations and window properties; these were denoted as Model 1L (the air supply register located under a

low-insulation window), Model 1H (the air supply register located under a high-insulation window), Model 2L (the air supply register located near the centre of the ceiling, and a low-insulation window), and Model 2H (the air supply register located near the centre of the ceiling, and a high-insulation window). The temperature, PMV, and heat transfer comparisons are discussed below.

### **Temperature distribution and flow field inside the office**

We used the steady simulation approach in Autodesk CFD to observe the office once it was heated to an average indoor air temperature of 23°C. Fig. 3 shows the vertical temperature distribution patterns crossing the user's position in the four model situations. As discussed above, the strategy of placing air supply registers under windows was designed to combat discomfort from cold drafts on the floor near external windows. This concept of vent placement was also demonstrated in the comparison between vertical air temperature variations in Figures 3 (a) and (c). Models 1L and 2L had the same types of windows, but Model 2L clearly presented higher vertical temperature variations. The air flow pattern in Model 1L illustrated that the cold air around the window quickly merged with the hot air from the air supply vents, facilitating an even distribution of indoor air temperature. However, when the window insulation increased (as in Models 1H and 2H), the contrast between different vent placements and vertical temperature variations sufficiently diminished. There were almost no vertical temperature variations in Model 2H. This comparison revealed that there is no need to place air supply vents under exterior windows if those windows have strong insulation abilities.

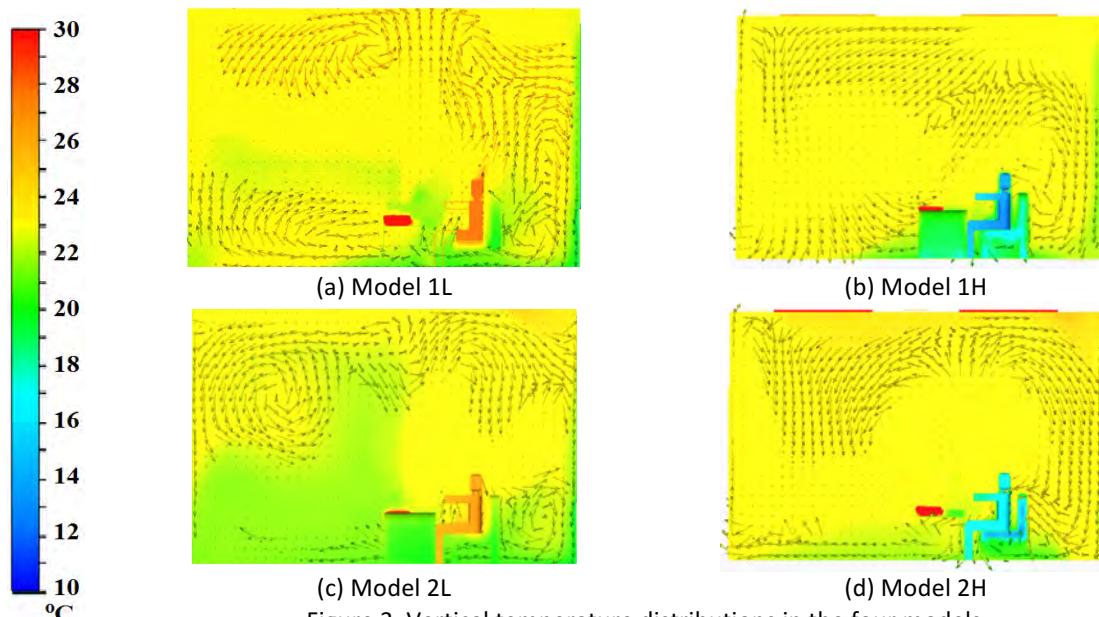


Figure 3. Vertical temperature distributions in the four models.

### **PMV analysis**

The PMV index uses a seven-point thermal sensation scale that is calibrated to the thermal perception of human bodies (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold)(ASHARE 2013). In this simulation study, we used default values for clothing insulation and metabolic rate. From the Autodesk CFD simulation, we extracted user PMV index distributions for the four models at 23°C; these are shown in Fig. 4. Compared with the under-window vent placement in Model 1L, the central placement in Model 2L caused a significant variation in the PMV index, even though the average value was still approximately

neutral. Similarly, the highly insulated windows in Models 1H and 2H had a very slight effect on the PMV index. Finally, the overall PMV index for the two models with triple-pane windows was more uniformly distributed across the user's body surface, as compared to Models 1L and 2L (with single-pane windows).

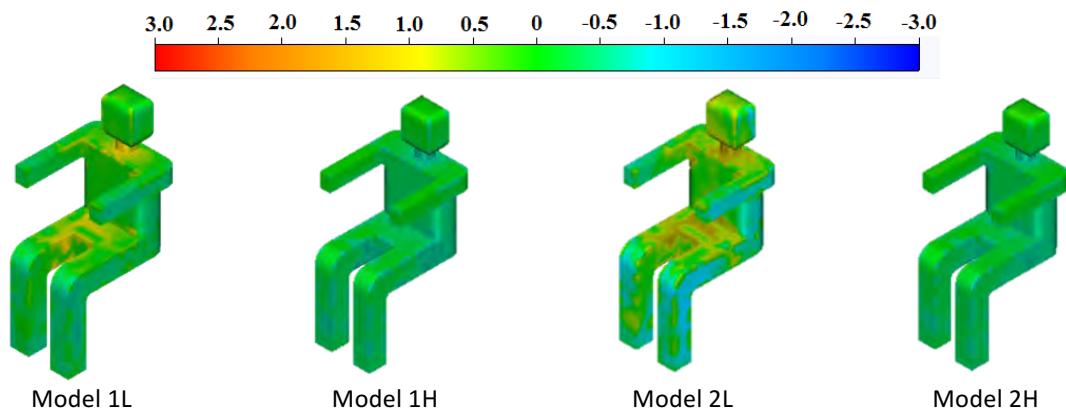


Figure 4. PMV index values for the four models.

#### ***Heat loss through windows***

Except for the exterior windows, all other model boundaries in this study were set as adiabatic material, so that the output heat transfer by the CFD simulation was only through the windows. As expected, Models 1H and 2H with highly insulated windows achieved significant heat loss reductions, approximately 41% and 40% over Models 1L and 2L with low-insulation windows, respectively (see Table 2). This can be explained by the approximately eightfold increase (i.e., from  $5.6 \text{ W/m}^2\text{-K}$  to  $0.65 \text{ W/m}^2\text{-K}$ ) in window insulation. Conversely, with regards to air supply vent placement, locating vents under exterior windows (as in Models 1L and 1H) resulted in more heat loss than the central placement seen in Models 2L and 2H; the difference was approximately 11%. In reality, if the air supply vent is placed under an exterior window, there would be a strong convective heat transfer between the warm air and the cold window's interior surface in winter, due to the high air speed and significant temperature difference.

Table 2. Heat Loss through Exterior Windows

	Model 1L	Model 1H	Model 2L	Model 2H
Heat transfer (W)	308.38	183.41	274.7	163.62

#### **Conclusions**

The present work was conducted to examine spatial variations in indoor air temperature and thermal comfort, and the corresponding heat transfer under different vent locations in a private office during the winter season in Cincinnati, OH, USA. Extensive CFD simulations and related studies were performed on four combinations of conditions: Models 1L, 1H, 2L, and 2H; each featured different vent locations and levels of exterior window insulation. From the simulation results, we concluded that placing air supply vents under exterior windows was clearly effective for achieving a more uniform air temperature distribution (as shown in Figure 3) and thermal comfort conditions (as shown in Figure 4) when low-insulation windows were in use. Although such placement caused more heat loss (about 11% more than the values resulting from central placement), this strategy has widely been used in office and residential buildings since the middle of the previous century. Nevertheless, under high-insulation window scenarios (such as those in Models 1H and 2H), the air supply vent locations would not significantly affect spatial variations in vertical temperature and thermal comfort.

However, the heat loss difference between the two types of placement examined in this research was approximately 11% (Model 1H vs. Model 2H). Therefore, the results of this CFD simulation-based comparative study resolved our research question of whether conventional placement under exterior windows was still effective and necessary when contemporary, highly insulated windows are in use.

The findings from this research provide an improved understanding of how thermal comfort and energy issues change in response to different vent locations and types of building windows. It may also shed light on how to best optimize air vent placement and window design. Our future work will address the effects of thermal radiation by interior window surfaces with certain emissivity levels and the specific heat properties of boundary materials. We will also move beyond the single office scale to analyse energy use on a whole building scale, with different window settings related to window-to-wall ratios, insulation levels, surface temperatures, etc. The implication of the vent placement and window type for indoor thermal conditions and energy use in summer season will be also studied in the future.

### Acknowledgements

We acknowledge the financial supports provided from the National Science Foundation (*CMMI - 1635089: The Photothermal Effects of Iron Oxide Nanoparticles on Energy Efficient Windows*) and the Environmental Protection Agency (*P3 Phase II - SU836940: Sensible Home: Micro-environmental Control through Wearable Personal Sensors*).

### References

- ASHARE, 2013. ASHRAE Standard 55-2013 : Thermal Environmental Conditions for Human Occupancy. *American Society of Heating, Refrigeration and Air conditioning Engineers*, ASHRAE Sta, p.58.
- Azizpour, F. et al., 2013. Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Centre (UKMMC). *Energy and Buildings*, 64, pp.317–322. Available at: <http://dx.doi.org/10.1016/j.enbuild.2013.05.033>.
- Carletti, C., Sciuropi, F. & Pierangioli, L., 2014. The energy upgrading of existing buildings: Window and shading device typologies for energy efficiency refurbishment. *Sustainability*, 6(8), pp.5354–5377.
- Carrier, C. & Air, ny C.A.C., 1965. *Handbook of air conditioning system design*, McGraw-Hill.
- Cheng, Y., Niu, J. & Gao, N., 2012. Thermal comfort models: A review and numerical investigation. *Building and Environment*, 47(1), pp.13–22. Available at: <http://dx.doi.org/10.1016/j.buildenv.2011.05.011>.
- Fanger, P.O., 1972. *Thermal Comfort* New York.
- Ferreira, P.M. et al., 2012. Neural networks based predictive control for thermal comfort and energy savings in public buildings. *Energy and Buildings*, 55, pp.238–251.
- Grondzik, W.T. & Kwok, A.G., 2014. *Mechanical and electrical equipment for buildings* 12th ed., Wiley.
- Janis, R.R. & Tao, W.K.Y., 2013. *Mechanical and electrical systems in buildings* 5th ed., Pearson Education, Inc.
- Nicol, J.F. & Humphreys, M.A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and buildings*, 34(6), pp.563–572.
- Standard, A., 2013. *Standard 55-2013. Thermal environmental conditions for human occupancy*.
- Standard, I.S.O., 1994. 7730. *Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*.
- Wagner, A. et al., 2007. Thermal comfort and workplace occupant satisfaction-Results of field studies in German low energy office buildings. *Energy and Buildings*, 39(7), pp.758–769.
- Wang, J. et al., 2016, July. Selection of energy efficient windows for hot climates using genetic algorithms optimization. In *Proceedings of PLEA 2016, International Conference on Passive and Low Energy Architecture 2016: Cities, Buildings, People: Towards Regenerative Environments, Los Angeles*.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Impact of Technology and innovation on adaptation of architectonic tradition for a sustainable future in the Middle East**

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**Abstract:** The proposed study seeks to establish whether the community is in favour of environmental traditional architecture despite the increase of modern architecture and its subsequent benefits such as indoor thermal comfort. Globally, traditional architecture has a lot of values. In the Middle East (ME), it shows the way people lived in an area and translate their requirements in a distinctive character.

The old architecture carries in it very rich design features which if learned and adopted could immensely help in bringing change to current architectural designs. Thomas (2002) maintains that it is important for the Arab world to revisit all their traditional typologies. Sustainability is expected to remain high with the revealing of old identify architecture to current one. The current study is based on the fact that there is an increase in international-based engineers, who are not able to construct building in line with the cultural aspects of the local users in the ME. However, the question remains on whether and how technology and innovation can be utilized to preserve the architectonic traditions intertwined with modern architecture for a sustainable future in the ME.

This research attempts to contribute to the environmental design for an improved human well-being in the ME.

**Keywords:** Environmental traditional architecture, Thermal comfort, Transitional architecture

### **Introduction**

There has been a wide range of studies on the intersection between traditional architecture and modern approaches to building and construction. The debate has always been how to balance between the benefits of traditional and modern and often western architectural approaches. Ideally, the choice of architectural approach should be driven by factors such as social environment, religious practices, cultural factors and economic aspects. In this regard, architecture is expected to be authentic and sustainable to the local environment. At the same time, adopted architectural approaches should be adequately progressive in terms of adoption of latest construction technologies.

### **Rationale of the study**

The proposed study seeks to establish whether the community is in favour of environmental traditional architecture despite the increase of modern architecture and its subsequent benefits such as indoor thermal comfort. Globally, traditional architecture has a lot of values. In the Middle East, it shows the way people lived in an area and translate their requirements in a distinctive character. Bukhash (2001) argues that these architectonic traditions need to

be learned, handled, conserved and improved in modern building practice and planning policies.

### **Statement of problem**

Since 1970's there has been high growth in the Middle East population. This growth has led to increased demand of housing and the local builders and architects have not responded due to various limitations. Such limitations include shortage in number of local engineers, construction needed in shortest time possible among others. The shortage of the engineers was filled by international expertise who could not respond to cultural aspects of local users. This has caused the decline of traditional architecture in the Middle East. The researcher wants to look at how innovation and technology can help in adapting architectonic tradition for a sustainable future in the Middle East.

### **Research Aims and Objectives**

#### **Aim**

The research aims to assess environmental traditional architecture in its modern context to understand people's physical (thermal heat) and psychological needs and preferences. People preferences in term of which trend will give the occupants indoor and outdoor comfort on the level of sustainability and climate change which also affect the policies of the city. The research also aims to demonstrate the legitimate use of traditional domestic environmental architectonic features in the Middle East. A third aim is to measure building performance with focus on what is appropriate for housing application based on climate control/ thermal comfort as an indicator and other psychological components to a limit to validate psychological and physical inputs; space with different typology/ scheme will be the unit of analysis.

#### **Research Objectives**

- To recognize the importance of the presence of environmental traditional architecture in the indoor environment, and their importance to their thermal comfort.
- To study the environmental traditional techniques and modern technology applications, which can enhance buildings designed and in-use performance based in the Middle East
- To explore the impact of the balance between traditional architecture within a contemporary context on the occupants and the building performance; quantifying measurements for the study results.

### **Literature Review**

#### ***Collaboration of Modern architecture and traditional value/designs***

In the Arab World, a re-evaluation traditional system would assist policy makers to reclaim their identity and pride as well as restore them with their people and prepare them to be or better service. Traditional architect has boundless potential in the Middle East as a source of informing modern architecture. According to Al-Mansouri and Al-Naim (2005), traditional architecture provides endless practices that modern architecture can draw inspiration from. Therefore, collaboration between modern architecture and architectonic traditional designs should be encouraged.

With regard to sustainability, it is important that countries in the Middle East have re-examined traditional models to expose identity to modern architecture. Rashid (2004) argues that this rising concern towards traditional architecture is among a more general concern to preserve historic buildings since they are antique documents and traces of historical forms of art. In view of this, it is vital for their integrity to be conserved and refurbished object be of authenticity.

### ***Sustainability and traditional architecture***

In the early century people living in the Middle East heavily depended on the natural world to learn some very common guiding principles that encouraged sustainability. Architects believe that current human population can also learn a lot using the same principles which can encourage environmental sustainability (Asfour, 1998). In the past people used to live in very comfortable environments, they had no problem with social, cultural or climatic condition. This is one thing current humans needs to learn. There three major features which predominantly dominated any decorative and design feature in the early human life, these were privacy, security and temperature control.

For example, colonnades and courtyard remained two very important aspects. The former provided ventilation and indirect light to living areas while the latter provided shelter from both sun and wind. Regional architectures heavily considered doors, columns, capitals, roof parapets, shutters, windows, screens and wind-towers as their common motifs. Asfour (1998) believes that literature lacks sufficient traditional architecture on the Middle East world. Coming up with eloquent architectural design similar to those used in the past would literally mean a complete overhaul of current architectural designs. One perfect way of making this a reality dream is by encouraging current architectural students to adopt a traditional learning mind. This will help the students to compare and contrast old historical settings with the current ones to come up with very perfect solutions.

### **Method and Research Approach**

The researcher will emphasize in this paper on the quantitative data collected from one of the selected spaces for the experiment, in relation to cultural existence and change in Riyadh, Saudi Arabia.

The data presented in this paper was collected from Landform House; a private house for Dada architecture firm. The data loggers were placed in three different spaces or themes; indoor modern scheme living house; indoor transitional scheme tea room space and outdoor space created similar to the traditional Petra path "Al-Seeq". A second set of data was collected from Historical Addiriyah from three data loggers as well; indoor traditional living, traditional court and the outdoor area, however, this set of data is not covered in this paper. The initial data analysis is translated in this paper in terms of psychological comfort looking for public acceptance and resistance, to ensure findings are compatible with environmental housing application in Hot-Arid climate of the Arab region.

According to Bryman & Bell (2011) a theme comes into place when one tries to capture the fundamental importance or meaning of a select component of the narrative text. For this study, the researcher will rely on the themes as the main backbone on what the study is trying to bring out.

### ***Instruments***

Three data loggers were located in three areas, the first is a living room that is constructed in a modern architectural design involving big glass facades.



Figure 1. Landform House, Living Room

The second area is a tearoom built in a transitional scheme merging the modern structure with one of the traditional architectonic features; a cooling tower as shown below.



Figure 2. Landform House, Tea Room

The third logger is placed outdoors to compare indoor and outdoor temperatures.



Figure 3. Landform House, Outdoor

### ***Discussion***

Three data loggers were situated in three different spaces; outdoor; living room and tea room. The data displayed in figures 1, 2, and 3 are collected over a three months period from April until June, 2016. As stated by Records of annual temperature (1996) in Riyadh, Saudi Arabia; between March and April is spring with heavy short rain falls; from mid-April till October moderate to hot summer. Therefore, its Hot-Arid architectural zone relative to being close to equator. According to Riyadh code standards human level of comfort in the outdoor in the central region of Riyadh is between 20 °C to 30 °C.

The line graph representing the temperature outdoors shows an average temperature of 28 °C during April with the least temperature of 19 °C and a peak temperature of 46 °C. In comparison to the temperature in the living room, the average is 27.9 °C with almost same degree with the outdoors during the same month. However, the coolest area during April was the tea room with an average of 27 °C which is almost 2 degrees less than the living room and the outdoors, that represents the effect of the windcatcher architectonic feature.

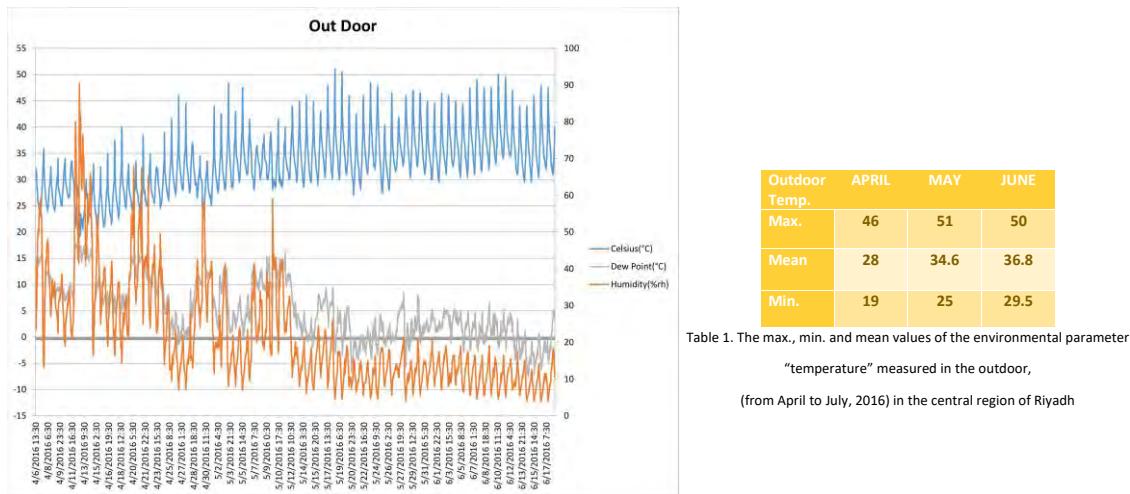


Figure 4. Graph of monthly and hourly record of the environmental parameter "temperature" measured in the outdoor, in summer (from April to July, 2016) in the central region of Riyadh

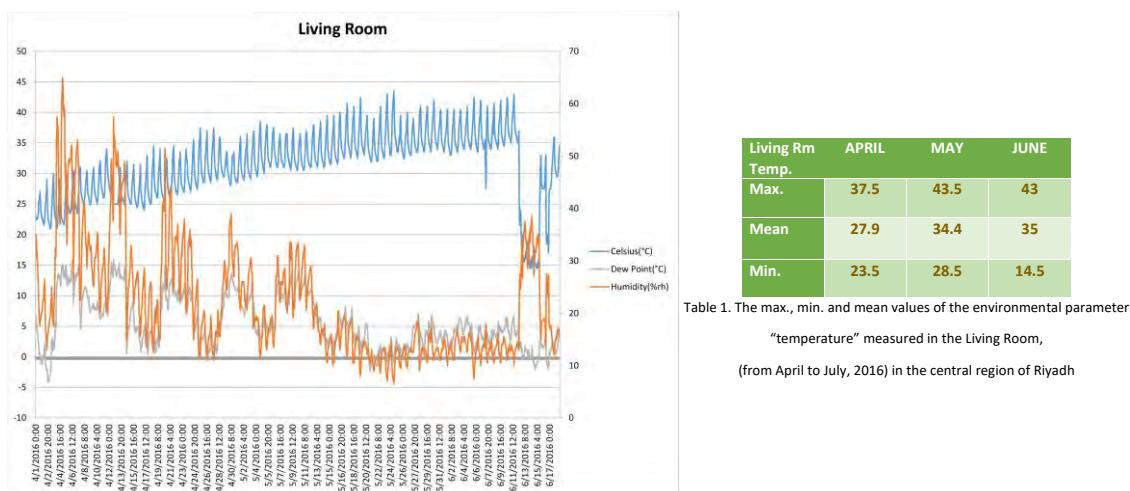


Figure 5. Graph of monthly and hourly record of the environmental parameter "temperature" measured in the indoor living room, (from April to July, 2016) in the central region of Riyadh

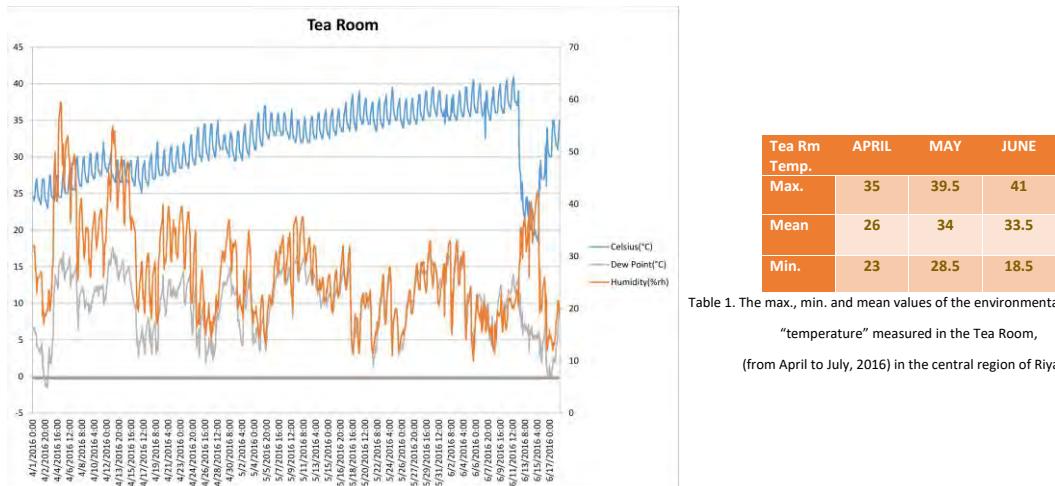


Table 1. The max., min. and mean values of the environmental parameter "temperature" measured in the Tea Room, (from April to July, 2016) in the central region of Riyadh

Figure 6. Graph of monthly and hourly record of the environmental parameter "temperature" measured in the indoor Tea Room, (from April to July, 2016) in the central region of Riyadh

The outdoor area was selected with in the house for the study relevance. The space was designed in a way to create a cross ventilation through the house cooling its spaces, this made the graph readings even cooler than the existing outdoor temperature.

The trend of the Time Series Graph is mostly similar for all three months, reflecting an efficacious reduce of the indoor temperature; of the windcatcher, a traditional environmental feature adapted into modern scheme, along different seasons; spring and summer including moderate and hot weather. Hence the temperature with the use of traditional environmental features are always pleasant to the occupant level of comfort.

#### *Limitations*

This study was done in the central region of Riyadh, Saudi Arabia; due to the limited no. of loggers/devices available which makes its finding limited to the climate of the selected area which is Hot-Dry climate. Therefore, more studies are required to generalize the results of the study on the ME. Arab Region. Occasionally temp. in the living room is cooler than the tea room this could be contributed to the air-conditioning factor that could affect the result slightly. It is not enough in hot summer since daytime temperatures frequently exceed 40 °C; but fall at night, and the presence of strong wind carry desert sand with them, to rely only on the fresh air ventilation.

#### **Conclusion**

The paper is presenting a study that is part of a PhD. Research and further analysis will be transcribed in detail in the full thesis, where the results will be explored in relation to human psychological and physical comfort.

To understand different approaches of the research shall extend the thermal study in relation to human psychology, and in different climatic architectural zones to include another areas of the Arab Region.

To conclude on hot-dry climate; temperature is reduced with the use of traditional environmental features, from the outdoor and from modern spaces using electrical air-conditioning system in relation to human level of comfort. As they are often supporting occupants' comfort during most of the day time. This sustainable development among traditional and modern themes will allow for long-term benefit for all mankind.

## References

- Al-Mansouri, M. & Al-Naim, M. (2005) Modern Architecture in UAE: A Study to Early Transformation in City before Declaration of the Federation, Architectural & Planning Journal, Vol.16, PP.83-100
- Asfour, K., (1998 ) Architecture Discourse in the Arab World, Sustainable Architecture and Construction for the Middle East Conference, conference booklet, March 30-31, 1998, Abu Dhabi, UAE.
- Bryman, A. and Bell, E., (2011). Business research methods. Cambridge: Oxford University Press.
- Bukhash, Rashad. (2000) *Managing Restoration Projects in Dubai* - United Arab Emirates, M. Phil. thesis submitted to the Faculty of Art, University of Manchester, UK.
- Creswell, J. and Creswell, J., (2007). Qualitative inquiry & research design. Thousand Oaks: Sage Publications.
- DADA, A., 2013. 3 Case Studies Comparative Analysis, LandForm House: The Other Dada.  
*Oxford Encyclopedic World Atlas, Reed, London, 1996*
- Ragette, F. (2012). *Traditional Domestic Architecture of the Arab Region*. Third, unrevised edition. Sharjah: Axel Menges.
- Thomas, D. (2002), Architecture and the Urban Environment: a Vision for the New Age, Architectural Press, Oxford, UK.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Field Investigation on Unacceptable Sensation of Thermal Environment in Taiwan Office

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**Abstract:** The average thermal sensation of occupants in the hot and humid region of Asia is different from that of Europeans and Americans. Office occupants in buildings equipped with air conditioners tend to find the thermal environment uncomfortable due to individual differences of thermal sensation. In this research, the thermal environment was measured in two office buildings in Taipei during summer. The Occupants' sensation of the thermal environment was recorded using a voting machine developed by team researchers. Thirty-six occupants were requested to report the feeling of an unacceptable thermal environment by pressing a red or blue button on the voting machine when feeling hot or cold, respectively. The results show that operative temperature and absolute humidity varied at the times an individual was out of the comfort zone based on ASHRAE Standard 55(2013). Although all individuals were in the same environment, some occupants reported feeling unacceptably, even though they were at a temperature and humidity level considered to be within the comfort zone. About 60% of unacceptable votes reported feeling cold while within the comfort zone. This research suggests that it is possible to revise existing comfort criteria in offices in Taiwan or other hot or humid regions in Asia.

**Keywords:** Thermal comfort, Occupant sensation, Unacceptable sensation, Air conditioned office space, Tropical Region

### Introduction

Countries in the hot and humid regions of Asia contain one third of the world's total population. Future energy consumption is predicted to increase because of economic growth, thus energy-saving strategies are an important topic in this region. High-rise buildings with glass façades have increased rapidly in recent years in Southeast Asia, and their Heating, Ventilation, and air conditioning (HVAC) system planning and façade design of office buildings in this region is based on American or European standards. However, these standards were developed in America and Europe, which have relatively colder climates. The thermal sensations of people in South-East Asia are different from people in the West, owing to difference of climate and lifestyle in each region (Nakano, J., et al, 2001). Thus, office spaces are likely to cause occupants to feel unacceptably hot or cold due to individual differences of sensation.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55(2013) is based on a thermal equilibrium model verified in an environmentally controlled room. Capacity and operating condition of installed HVAC systems is designed to conform to the thermal comfort criteria in the standard. However, it is difficult to keep a

uniform thermal environment in office spaces due to the influence of the outdoor environment and heat generated internally. Using this standard, it is hard to evaluate the thermal environment in practice. When evaluating the thermal environment, we need to record the occupants' thermal sensations in real time to complement the standard.

In this study, the thermal environment was measured in two Taipei office buildings (Office 'F' and Office 'L') during summer. Taiwan must import more than 99% of its fossil fuel resources, and is required to rely on fossil fuels and renewable energy because of the unstable political factors regarding nuclear power generation. Therefore, policies to reduce electric power consumption are promoted in this region. In 2010, electricity use in the service industry was equal to the residential use. This situation makes it necessary to investigate the actual state of the thermal environment in general office spaces. This study aims to determine the occupants' perceptions of feeling unacceptably hot or cold in a Taipei office. We measured the thermal environment, and conducted an unacceptable sensation survey and a questionnaire survey (Miura, T., et al, 2001).

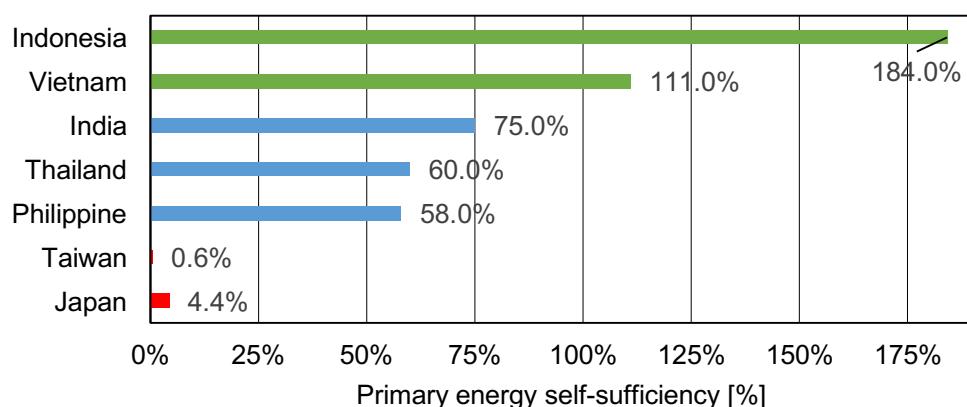


Figure 1. Primary energy self-sufficiency in South-East Asia (2010; except nuclear power)  
(Bureau of Energy, 2010. The Institute of Energy Economics, Japan, 2013)

## Method

### **Target office**

Measuring the thermal environment and the occupants' feelings of being unacceptably hot or cold was necessary to determine how the thermal environment affects the occupants' thermal sensations. Data was collected during the summer of 2016 using voting machines and a questionnaire survey. Table 1 and Table 2 shows period of investigation, survey subjects and an overview of the target offices.

Table 1. Period of investigation and survey subjects

		Office F	Office L
Period of investigation	Thermal environment	2016/9/5-14	2016/9/6-15
	Unacceptable sensation investigation period	2016/9/5-10	2016/9/6-9
	Questionnaire investigation	2016/9/8-14	2016/9/7-14
Survey subjects (Male : Female) [people]		17 (9:8)	19 (12:7)

Table 2. Target building overview

	Office F	Office L
Total stories in the building	17	12
Target story	15	10
Gross area [m <sup>2</sup> ]	11832	9158
Target office area [m <sup>2</sup> ]	257.1	544.7
Target office Window area [m <sup>2</sup> ]	43.4	46.7
Number of occupants	36	62
Structure system	Steel	RC
HVAC system	Multiple packaged AC unit systems	Individual AC systems
Target temperature [°C]	26	24-27

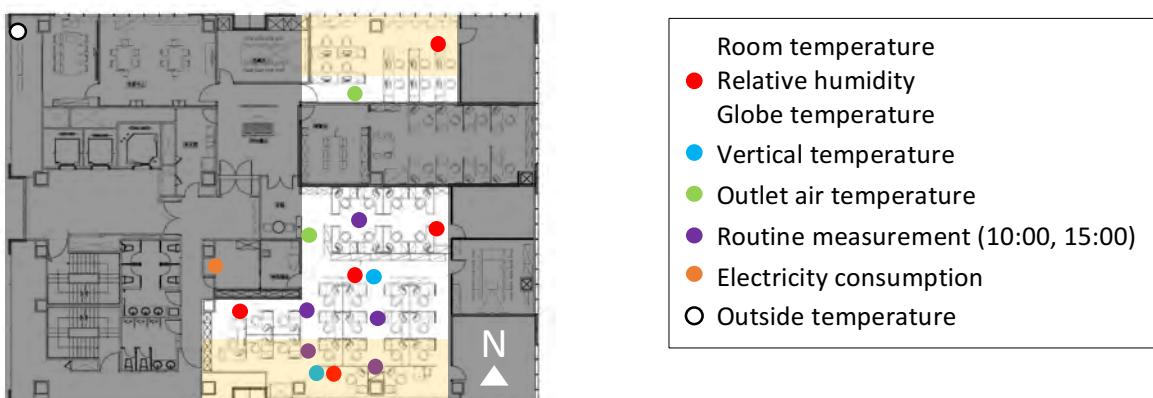


Figure 2. Floor plan of office F

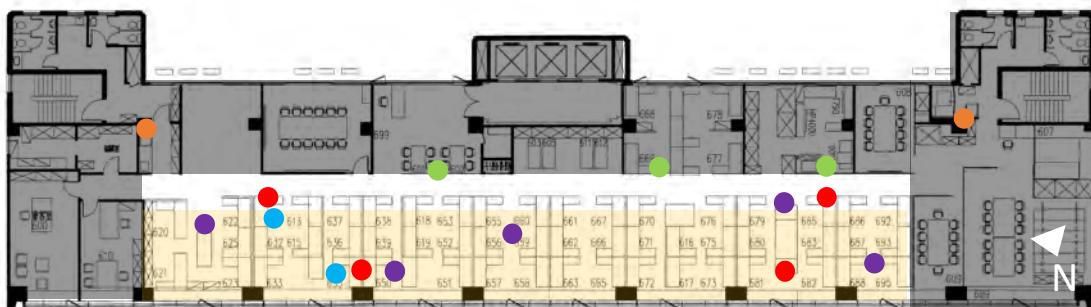


Figure 3. Floor plan of office L

### ***Unacceptable sensation survey***

Sensations of occupants feeling unacceptably hot or cold were investigated using voting machines developed by team researchers (Saito, S., et al, 2014). Twenty machines were distributed to occupants working in the office during normal business hours, and installed on each desk. Figure 4 show the appearance and circuit diagram of the voting machine. This machine records two kinds of unacceptable sensations, which are either those of feeling “too hot” or “too cold”. Thirty-six occupants were requested to report the instance that they felt unacceptably hot or cold by pressing a red- or blue button on the machine. The voting

machine recorded when the button was pressed and the thermo-hygrometers inside it recorded the thermal environment.

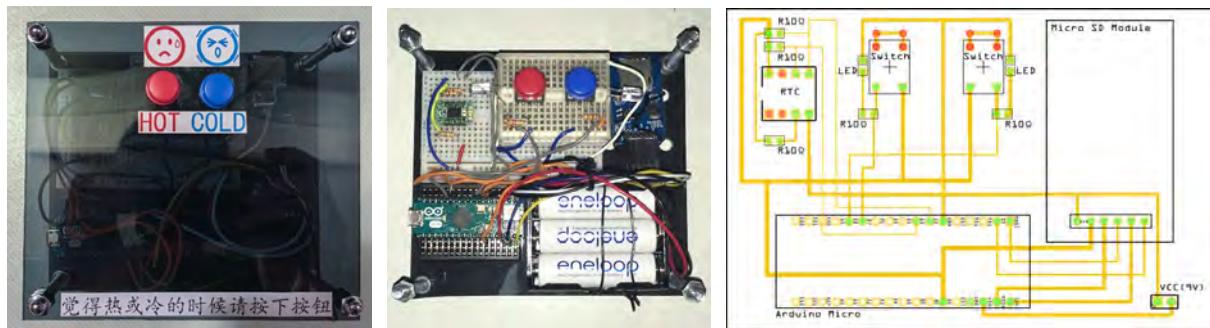


Figure 4. Appearance of voting machine and its circuit diagram

### **Questionnaire survey**

The questionnaire survey was conducted simultaneously with other surveys. Occupants answered this questionnaire at 10:00 and again at 15:00. Table 3 lists the questionnaire survey items (Tokuda, E., et al, 2016). This questionnaire was translated from Japanese to Chinese by team researchers. Neutral temperature was calculated using Griffith's method.

Table 3. Questionnaire overview

Personal Data
Age / Gender / Weight / Height / Health condition / Clothing / Seat position
Thermal Sensation
Thermal sense vote (Hot , Warm , Slightly warm , Neutral , Slightly cool , Cool , Cold )
Dry or wet sense (Humid , Neutral , Dry)
Comfort (Very comfortable , Comfortable , Neutral , Uncomfortable , Very uncomfortable)
Acceptance (Acceptable , Unacceptable)
Adjustment (More warm , No change , More cool)

### **Indoor environment**

On the same days as the investigation of unacceptable sensation and the questionnaire survey were performed, the thermal environment was also investigated. Temperature, relative humidity, and globe temperature were each measured for one minute at points 1100 mm from floor in both the interior and perimeter zones. Outdoor temperature and relative humidity were also measured for one minute each. Figures 4 and 5 show measurement points in offices F and L.

### **Result**

#### **Thermal environment and unacceptable sensation votes**

Figure 5 shows a psychrometric chart of both the operative temperature and absolute humidity measured in two offices during working hours (8:00-17:00), and the comfort zone based on ASHRAE Standard 55(2013). As thermo-hygrometers measure only room temperature, we regard it as operative temperature. Measured values of operative temperature and absolute humidity were both inside and outside of the ASHRAE standard

comfort zone. Votes recording unacceptable sensation occurred not only in the zone but outside of it as well.

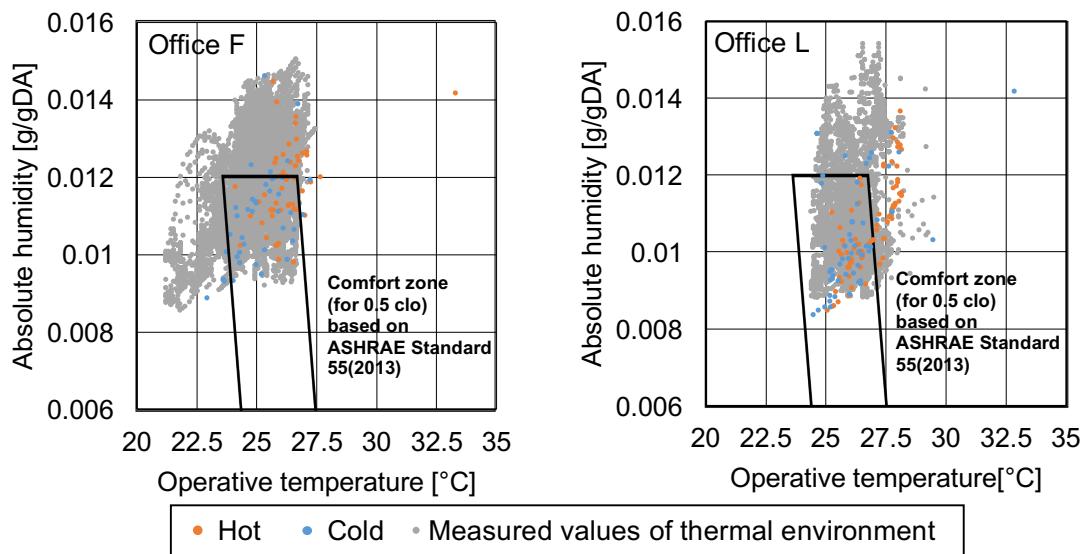


Figure 5. Thermal environment around desks, unacceptable sensation report and comfort zone based on ASHRAE Standard 55(2013)

### **The number of votes per hour per device**

Figure 6 shows the number of unacceptable sensation votes per hour per device. The number of hot and cold votes in each office was nearly equal. The average votes per device per hour value of previous studies in Japan is 0.16 (Ichikawa, S., et al, 2014). The corresponding value of office F is close to the value in Japan, but value of office L is about three times the Japan value. Office L had been built as a collective house about forty years ago. After some time, it was renovated as an office. Thus, it was presumed that changes to the HVAC plan and environmental performance during renovation influenced the building's thermal comfort.

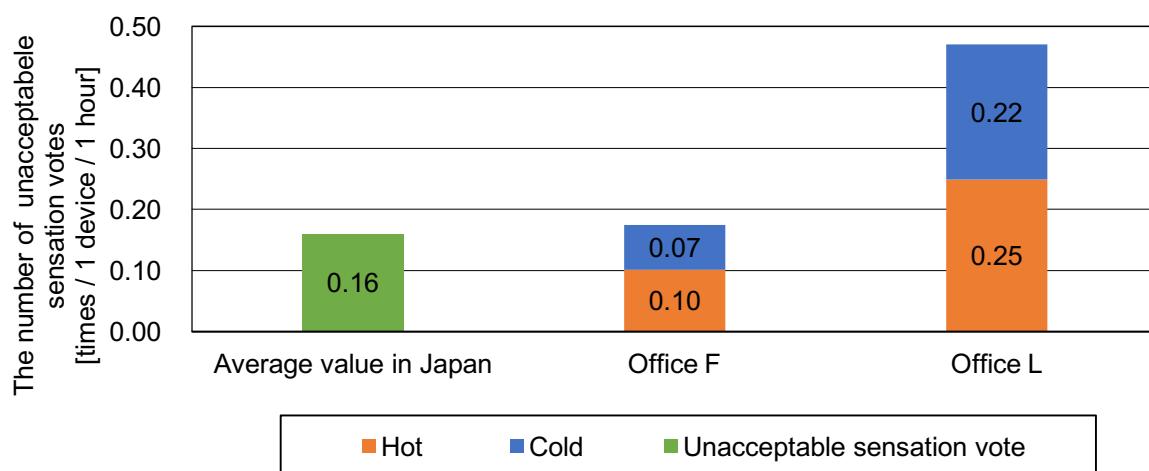


Figure 6. Number of unacceptable sensation votes per hour per device

### **Trend in the average number of votes per device**

Figure 7 shows the trend in the average number of unacceptable sensation votes per device and the average room temperature each hour in both offices. The room temperature in the

morning (8:00-10:00) was higher than at other hours. Most votes indicating it was too hot were concentrated around 9 o'clock owing to the thermal environment at the start of air conditioning operation and worker commute. As the number of hot votes was linked with trend in the average room temperature, the relation between thermal environment and votes could be confirmed.

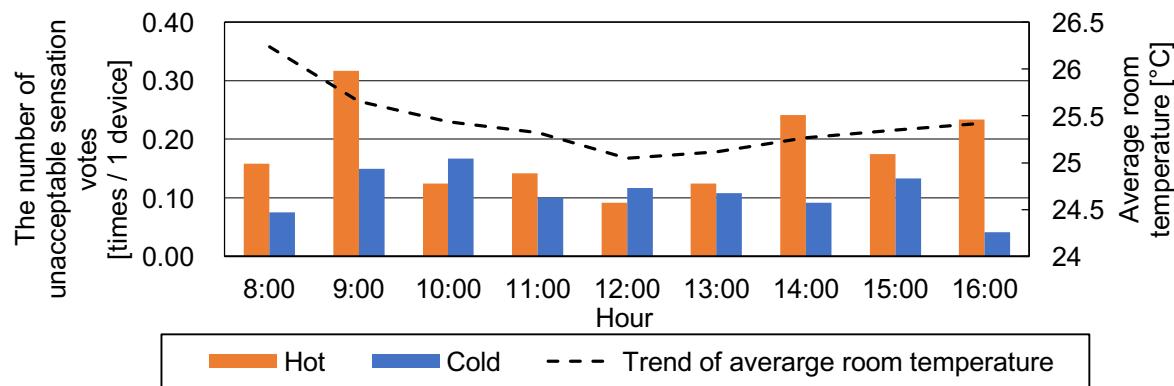


Figure 7. Trend in the average number of unacceptable sensation votes per device

### ***Breakdown of votes***

Figure 8 shows the breakdown of unacceptable sensation votes in both offices. About half of all votes occurred while ambient temperature was in the comfort zone. About 60% of all votes in the zone indicated that the voter felt too cold. Therefore, occupants tend to feel cold in thermal environments complying with the ASHRAE standard. There was a possibility that environmental elements aside from temperature and humidity affected thermal sensation.

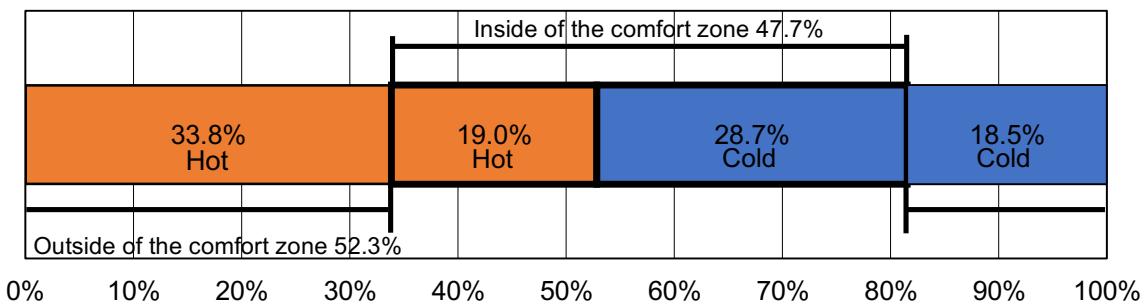


Figure 8. Breakdown of unacceptable sensation votes

### ***Occurrence frequency of votes and room temperature***

Figure 9 shows the occurrence frequency of both unacceptable sensation votes and room temperatures. In both offices, hot sensation votes were weighted toward the high temperature side and cold sensation votes were weighted toward the low side. Thus, the relation between room temperature and complaints can be verified. It was presumed that occupants' thermal history, breeze from the air conditioners, and radiant heat affected the occurrence of complaints because hot and cold complaints were nearly equal at around 25 °C.

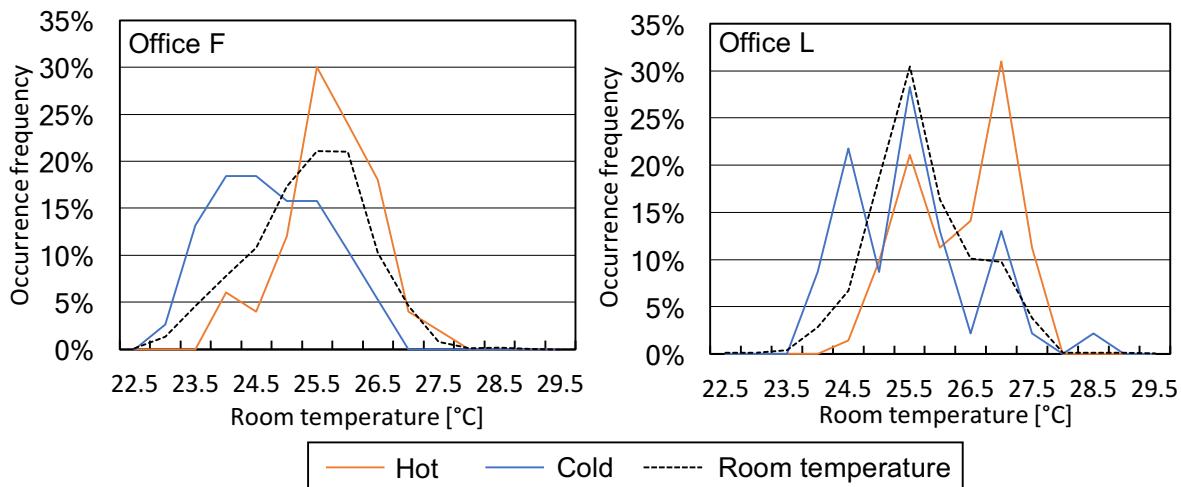


Figure 9. Occurrence frequency of unacceptable sensation votes and room temperature

### **Occurrence frequency of votes and globe temperature**

Figure 10 shows the occurrence frequency of unacceptable sensation votes and globe temperature. In both offices, hot sensation votes were slightly weighted toward the high temperature side and cold sensation votes were weighted toward the low side. This indicated that radiant heat from the building envelope influenced the feeling of being too hot. Moreover, breeze from the air-conditioning system is also an important factor influencing the feeling of being too cold.

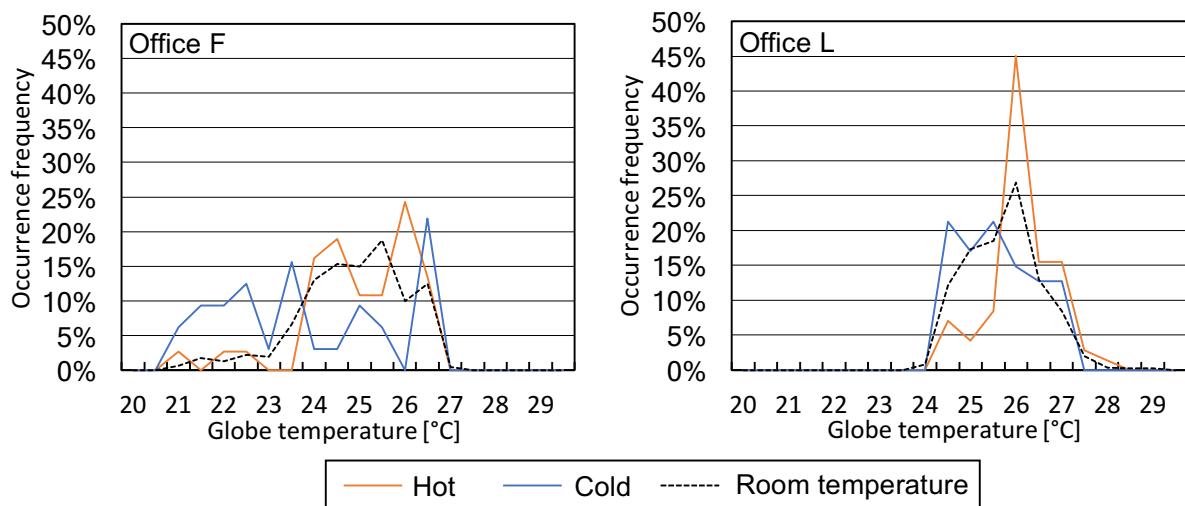


Figure 10. Occurrence frequency of unacceptable sensation votes and globe temperature

### **Neutral temperature**

We analysed the thermal neutral condition based on the questionnaire survey about occupants' thermal sensations. Figure 11 shows the distribution of neutral temperature and room temperature. In both offices, the interquartile range of room temperature was distributed on the low side of the neutral temperature range. Therefore, most occupants felt that the thermal environment in offices was generally acceptable. However, the tendency to feel cold was slightly higher.

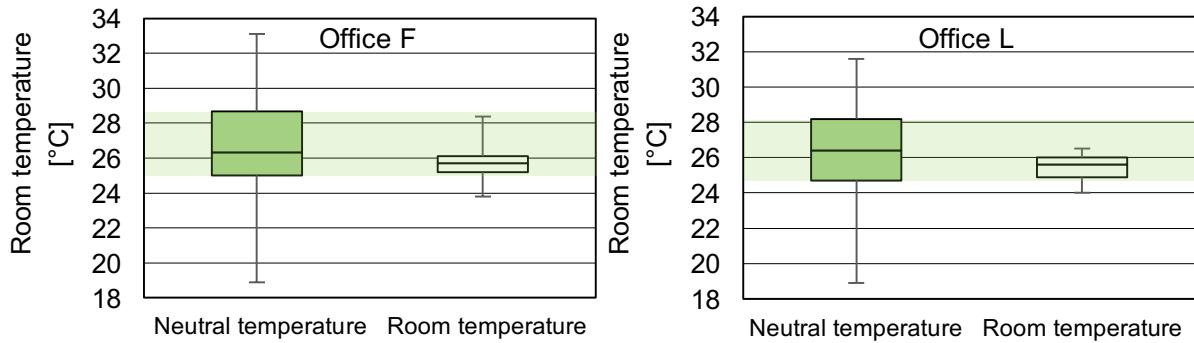


Figure 11. Distribution of neutral temperature and room temperature

## Conclusion

The thermal environment was measured and an unacceptable sensation survey using voting machines was conducted in two Taipei offices. About 60% of voters reported feeling cold, although the voter was in the ASHRAE standard prescribed comfort zone. This result suggests increasing the target temperature of rooms. In addition, the analysis of possible relationships between feeling too hot or too cold and globe temperature indicated that breeze from air-conditioning systems was an important factor influencing the feeling of being too cold. Radiant heat from the building envelope affected the feeling of being too hot. To sum up, this research suggests that it is possible to revise existing comfort criteria in offices in Taiwan or other hot and humid regions in Asia.

## References

- The ASHRAE Standard Committee. (2013). Thermal Environmental Conditions for Human Occupancy
- Nakano, J., et al, (2001). Field Survey on Thermal Environment, Air Quality, and Occupant Comfort in a High Density Heat load Office Occupied By Multi-National Workers. *J. Archit. Plann. Environ. Eng., AIJ*, 545, pp.45-50
- Miura, T., et al, (2001). The Correlations between Measured Physical Levels and The Occupants' Sensation Responses at Their Offices. *J. Archit. Plann. Environ. Eng., AIJ*, 539, pp.89-96
- Bureau of Energy. (2010). Energy Statistical Annual Reports
- The Institute of Energy Economics, Japan. (2013). IEEJ (2013.10)
- Saito, S., et al, (2014). Study on Acceptability in Thermal Environment (Part4) Influence of Attribute of Office Worker on Acceptability in Thermal Environment. The Society of Heating, Air-conditioning Sanitary Engineers of Japan, 88(6), pp.145–148
- Ichikawa, Y., et al, (2014). Study on Acceptability of Indoor Thermal Environment (Part1) Development of Ostoarcon and Field Study on Unacceptable Situation of Indoor Thermal Environment. Summaries of technical papers of annual meeting Architectural Institute of Japan, D-2, pp.417–418
- Tokuda, E., et al, (2016). Observational Study on TSV and Thermal Comfort in Office Building of Vietnam. In: 3rd ICIAP "Inclusive Space, Enriching Culture", International Conference of Indonesian Architecture and planning inclusive space, enriching culture. Daerah Istimewa Yogyakarta



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Are heavyweight buildings more comfortable? The potential of thermal mass in increasing thermal comfort

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**Abstract:** In temperate climates, one passive design solution is to increase the heat capacity of building fabric. This design principle aims to reduce heating demand in winter and over-heating in summer; it is also coupled with more stable indoor air and radiant temperature. This may suggest that by exposing thermal mass, occupants may feel more comfortable. Although previous research based on simulations have studied this relationship, there is a lack of empirical evidence. This paper reviews the results an EU-funded research project, smart controls and thermal comfort (SCATs) to ascertain the impact of building fabric on occupants' perceived comfort. Between 1997 and 2000, twenty-six office buildings from five different countries (France, Greece, Portugal, Sweden and UK) were surveyed using a transverse questionnaire, a longitudinal questionnaire and environmental monitoring. This paper analyses the transverse questionnaires responses (N=451), in particular answers to questions on thermal perception, thermal preference and overall comfort. Results show a statistically significant relationship between building fabric heat capacity and subjective comfort (thermal perception  $\chi^2(1)=3.78$ ,  $p=0.05$  and overall comfort  $\chi^2(1)=4.37$ ,  $p<0.05$ ). Heavyweight buildings are reported to be more comfortable than lightweight buildings. Providing careful integration with building management, this insight may have implications on the adoption of thermal mass in new and retrofit buildings.

**Keywords:** Passive design, Thermal mass, Thermal comfort, Adaptive comfort

### Introduction

Besides global mean surface temperature rising by at least  $1.5^{\circ}\text{C}$  by the end of the 21<sup>st</sup> century (IPCC, section 2.2.1, 2014), Europe is set to be faced with an increase in extremes climate events, in particular heat waves. Buildings will have to adapt to these new thermal conditions by applying mitigation strategies such as thermal mass, ventilation and solar shading (Hacker et al, 2005). Studies based on dynamic building simulations have shown that thermal mass has the potential to dampen indoor air temperature and therefore to reduce peaks in internal operative temperature leading to more comfortable indoor conditions (Aste et al, 2009; Tuohy, 2009; Arcuri et al, 2016). The aim of this paper is to investigate the potential of thermal mass in increasing thermal comfort using empirical evidence from an EU-funded research project, smart controls and thermal comfort (SCATs) (Nicol, 2001; Wilson et al, 2001; McCartney and Nicol, 2002).

The thermal mass effect is associated with the building's thermal capacity defined as the ability of a building to store and to release heat. In this paper, thermal capacity is used to compare heavyweight against lightweight constructions in non-steady state conditions, as temperature inside buildings vary in time and direction (indoor to outdoor and outdoor to indoor). In a temperate climate, the heat flows through the building fabric are not constant and unidirectional throughout the year or throughout the day. In summer, external temperatures may be higher than internal temperature during the day but lower during the night. These changes in heat flow result in a time shift between external and internal temperature, although both follow similar sinusoidal patterns. In summer, this delayed periodic transmittance in heat flow may alleviate the risk of overheating by absorbing solar and internal gains during the day and releasing heat at night. In this instance, the internal thermal mass should be ventilated at night, enabling it to precool before the next heating phase (Roucoult et al. 1999). As internal temperatures are damped during occupied hours, the first hypothesis is that heavyweight buildings are more comfortable than lightweight buildings in summer. However, this elemental approach does not take into consideration other building characteristics, such as air infiltration and ventilation strategies. Occupants may only perceive this dampening effect in buildings without mechanical ventilation and cooling (Holmes and Hacker, 2007). Therefore the second hypothesis is that heavyweight naturally ventilated buildings should be more comfortable than lightweight naturally ventilated buildings. Whilst the likelihood for more stable internal temperatures may lead to the assumption that heavyweight buildings are more thermally comfortable, this will certainly not always be the case and is dependent upon the interactions between the thermal mass and heating/ventilation systems, controls, scheduling and the external environment. As an example, without sufficient scheduling or set-back a heavyweight building will take longer to initially heat to comfort temperatures and may therefore be less comfortable than its lightweight equivalent over this period. Alternatively, within warm sunny periods any exposed thermal mass will help to absorb excess heat and reduce peaks in temperature. However, if this stored heat cannot be sufficiently discharged then the building is likely to experience significant and long term overheating (Roucoult et al. 1999). The predicted level of comfort therefore cannot be simply related to the thermal mass of a building but to the relationship of this mass to other aspects of the building fabric, systems and environment. Nevertheless, using statistical analysis across a wide enough dataset, overall trends are hoped to be established in this paper.

The first section will introduce the dataset and the data analysis methods applied. To follow, the second section will report on the results of the analysis. Finally the last section will discuss the findings and highlight implications to future building design.

### **Study design**

This paper aims to review the relationship between building thermal capacity and occupants reported thermal sensation, preference and comfort.

This paper analyses a dataset collected for an EU-funded research project on smart controls and thermal comfort (SCATs) (Nicol et al, 2002). Thermal comfort surveys were conducted in 26 non-domestic buildings across five countries and eight cities in Europe (France, Greece, Portugal, Sweden and the UK). The climate classifications of the eight cities are summarised in Table 1. The sample of buildings had five different ventilation types, including (NV) naturally ventilated (heating in winter, free-running, no cooling or mechanical ventilation in summer), (AC) centrally air conditioned (heating and cooling), (MV)

mechanically ventilated (no cooling in summer), (MM) mixed mode (heating in winter, cooling when needed in summer) and (PP) a mixture of AC and NV in the same building. Furthermore the sample of buildings had three different thermal capacity types, including lightweight (LW), medium- or mixed-weight (MW) and heavyweight (HW). For the purposes of this paper only LW and HW buildings were considered.

Table 1. Characteristics of the sample including building's thermal capacity (LW: lightweight, MW: medium- or mixed-weight, HW: heavyweight) and Köppen climate classification

Country	City	Thermal capacity	Köppen Climate Classification		
France	Lyon	2 HW, 2 MW, 1 LW	Group C - Temperate (Cfa)	Humid subtropical	
Greece	Athens	2 HW, 3 MW	Group C - Temperate (Csa)	Hot-summer Mediterranean	
Portugal	Porto	1 HW, 2 MW, 1 LW	Group C - Temperate (Csb)	Warm-summer Mediterranean	
	Afragida	1 HW	Group C - Temperate (Csa)	Hot-summer Mediterranean	
Sweden	Goteborg	1 HW, 2 MW	Group C - Temperate (Cfb)	Oceanic	
	Malmo	1 MW	Group D - Continental (Dfb)	Humid continental	
	Halmstad	1 LW	Group C - Temperate (Cfb)	Oceanic	
UK	London	1 HW, 5 LW	Group C - Temperate (Cfb)	Oceanic	

Surveys ( $n=4,655$ ) were carried out between June 1997 and October 1998. Concurrently to environmental monitoring, transverse questionnaires (at a single point in time) were completed, which applied questions on indoor environmental perception and preference, self-assessed productivity, use of environmental controls, clothing and activity level. This questionnaire was answered several times by the same participants in different seasons. For the purposes of this paper the results of three questions are analysed, including thermal perception (7-point scale), thermal preference (5-point scale) and overall comfort sensation (6-point scale).

The analysis method relies upon an unpaired sample, therefore the first step was to ensure independence of the data; i.e. each participant had only one observation which could have been completed during any season. Only the results of the first survey were retained for each participant ( $n=785$ ). MW buildings were removed from the sample, the final sample size was  $n=451$ . Then the results of the three questions were transformed into binary variables (see Table 2). With regard to thermal sensation, 'neutral' was presumed to be the desired thermal sensation, which is the case conventionally and has also been shown to be the "*commonest personal desired*" sensation (Humphreys, 2007).

Table 2. Coding the scales of warmth, preference and comfort

Code	Thermal sensation <i>How do you feel?</i>	Thermal preference <i>How would you prefer to feel?</i>	Code	Overall comfort sensation <i>How would you rate your overall comfort?</i>
0	Hot		1	Very comfortable
	Warm	Much cooler		Moderately comfortable
	Slightly warm	A bit cooler		Slightly comfortable
1	Neutral	No change	0	Slightly uncomfortable
	Slightly cool	A bit warmer		Moderately uncomfortable
	Cool	Much warmer		Very uncomfortable
	Cold			

The analysis applies methods for categorical variables by reviewing the number of occurrences that fall into each combination of categories. The first part of the analysis

reviews the distribution of thermal perception, thermal preference and overall comfort sensation for both HW and LW buildings. The second part of the analysis explores the relationship between two categorical variables (see Figure 1 Part A) using Pearson's chi-square test with Yate's continuity correction to avoid Type I error (identifying an effect that is not present). Finally the third part of the analysis explores the relationship between three categorical variables (see Figure 1 Part A and B) requiring a log linear analysis.

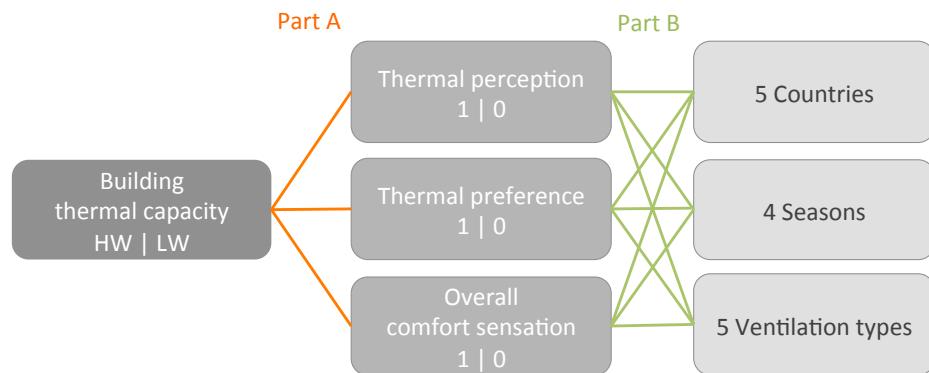


Figure 1. Map of the variables and relationships reviewed in this study.

## Results

The analysis explores participants' reported thermal perception (Tperc), thermal preference (Tperf) and overall comfort sensation (comfort). Interestingly at the time of the surveys, indoor air temperature in HW buildings (median=24.1°C) and in LW buildings (median=23.8°C) did not differ significantly,  $W=23655$ ,  $p=0.60$ . Furthermore the daily mean external temperature of HW buildings (mean=14.10°C,  $sd=5.70^{\circ}C$ ) and of LW buildings (mean=13.3°C,  $sd=4.9^{\circ}C$ ) did not differ significantly either,  $t(240.7)=1.5$ ,  $p=0.14$ .

### **Thermal perception**

Figure 2 shows that more participants reported to be thermally neutral in HW buildings (41%) than in LW buildings (32%); while more participants reported feeling cold, cool, slightly cool, slightly warm, warm and hot in LW buildings (68%) than in HW buildings (59%).

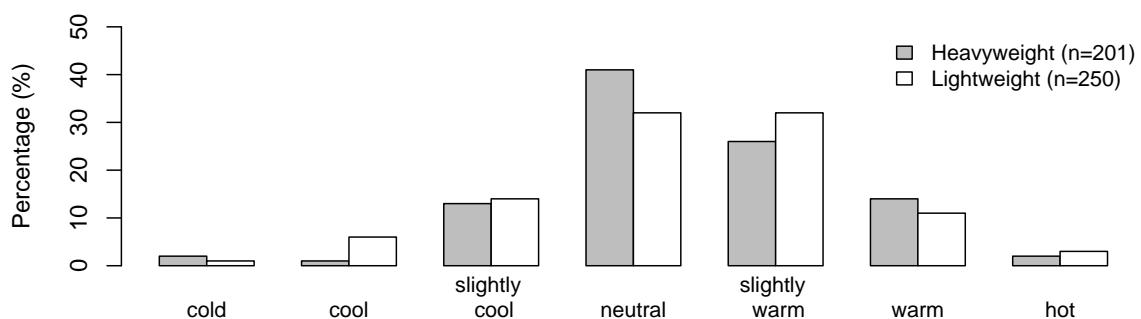


Figure 2. Distributions of thermal perception results for heavy and lightweight buildings.

Results of the first analysis show that there was a significant association between a building's thermal capacity and whether or not participants felt neutral,  $\chi^2(1)=3.78$ ,  $p=0.05$ . This seems to represent the fact that based on the odds ratio, the odds of a participant feeling thermally neutral were 1.5 (95% confidence interval: 1, 2.24) times higher if they were in a HW building than if they were in a LW building.

The three-way log linear analyses produced final models that include the interaction (capacity:Tperc:country), but dismiss the interactions (capacity:Tperc:season) and (capacity:Tperc: ventilation type). To breakdown these effects, separate chi-square tests on 'capacity' and 'Tperc' variables were performed separately for each country, season and ventilation type. The sample for Greece did not have any LW buildings; therefore the analysis could not be completed. For Sweden and the UK (oceanic climates), there was no significant association between buildings thermal capacity and thermal perception; however for Portugal and France there was a significant association, respectively  $\chi^2(1)= 9.55$ ,  $p<0.05$  and  $\chi^2(1)=5.1$ ,  $p<0.05$ . In Portugal, the odds of a participant feeling neutral were 6.86 times higher if they were in a HW building than if they were in a LW building. In contrast, in France, the odds of a participant feeling neutral were 3.89 times higher if they were in a LW building than if they were in a HW building. This result for France might be influenced by the different ventilation strategies applied in LW building (MV) and HW buildings (NV and MV). To review this potential effect, a subset of buildings with the same ventilation strategy (MV) for France was reviewed (see Figure 3). In this instance, results of the analysis of this subset (MV) shows that there was no significant association between buildings thermal capacity and whether or not participants felt neutral,  $\chi^2(1)=2.22$ ,  $p=0.14$ .

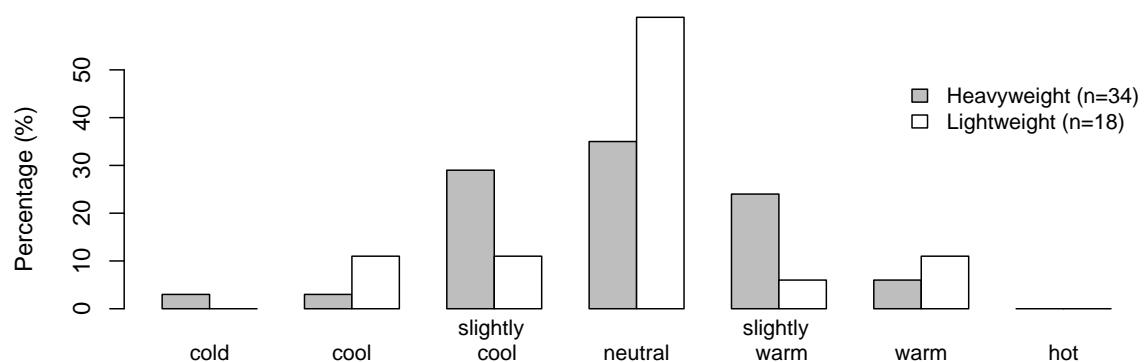


Figure 3. Distributions of thermal perception results for heavy and lightweight MV buildings in France.

For the four seasons, there was no significant association between buildings thermal capacity and thermal perception. The sample for (AC) and (MM) ventilation types did not have any HW building; therefore the analysis could not be completed. For (MV) and (PP), there was no significant association between buildings thermal capacity and thermal perception; however for (NV) there was a significant association,  $\chi^2(1)= 3.86$ ,  $p<0.05$ . Based on the odds ratio, the odds of a participant feeling neutral were 2.12 times higher if they were in a HW building than if they were in a LW building. To conclude there was a difference between ventilation types and countries but no difference between seasons.

#### **Thermal preference**

Figure 4 shows that slightly more participants preferred no thermal change in HW buildings (46%) than in LW buildings (43%), and more participants preferred cooler and warmer conditions in LW buildings.

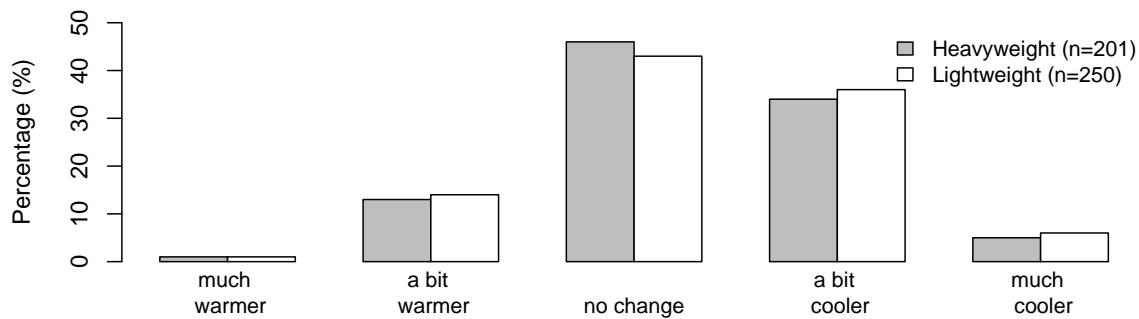


Figure 4. Distributions of thermal preference results for heavy and lightweight buildings.

Results of the analysis show that there was no significant association between buildings thermal capacity and whether or not participants wanted a change in thermal conditions,  $\chi^2(1)=0.31$ ,  $p=0.58$ .

#### **Overall comfort sensation**

Figure 5 shows that more participants felt comfortable in HW buildings (68%) than in LW buildings (58%), while more participants felt uncomfortable in LW buildings (42%) than HW buildings (32%).

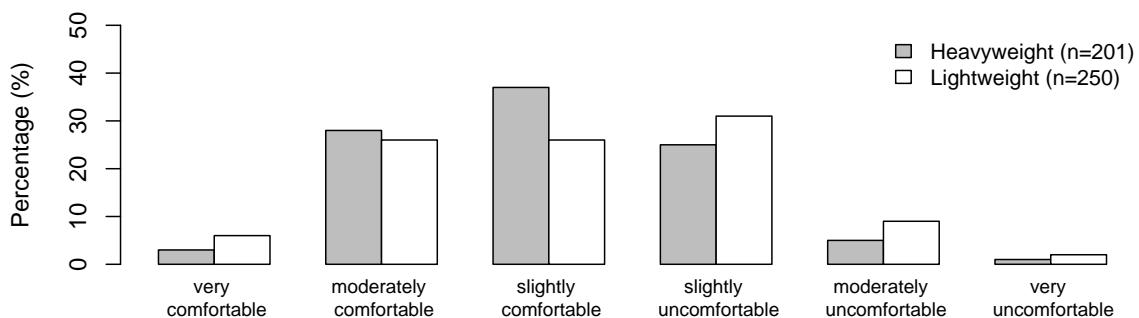


Figure 5. Distributions of overall comfort sensation results for heavy and lightweight buildings.

Results of the analysis show that there was a significant association between a building's thermal capacity and whether or not participants felt comfortable,  $\chi^2(1)=4.37$ ,  $p<0.05$ . This seems to represent the fact that based on the odds ratio, the odds of a participant feeling comfortable were 1.5 times higher if they were in a HW building than if they were in a LW building.

The three-way log linear analyses produced a final model that dismissed the interactions (capacity:comfort:country), (capacity:comfort:season) and (capacity:comfort:ventilation type). To breakdown these effects, separate chi-square tests on 'capacity' and 'comfort' variables were performed separately for each country, season and ventilation type. The sample for Greece did not have any LW buildings; therefore the analysis could not be completed. For the other four countries, there was no significant association between a building's thermal capacity and overall comfort sensation. For the four seasons, there was no significant association between a building's thermal capacity and overall comfort sensation. The sample for (AC) and (MM) ventilation types did not have any HW buildings; therefore the analysis could not be completed. For (MV) and (PP), there was no significant association between a building's thermal capacity and overall comfort sensation; however

for (NV) there was a significant association,  $\chi^2(1)=3.98$ ,  $p<0.05$ . Based on the odds ratio, the odds of a participant feeling comfortable were 2 times higher if they were in a HW building than if they were in a LW building. To conclude there was a difference between ventilation types but no difference between countries or seasons.

## Conclusions

Results show significant relationships between building thermal capacity and thermal perception, and between building thermal capacity and overall comfort sensation. However there was no relationship between building thermal capacity and thermal preference. If a participant was feeling warm or cool, he/she will want a change in thermal environment irrespective of the building thermal capacity. To answer the research question, heavyweight buildings were reported to be more comfortable than lightweight buildings. The odds of a participant feeling thermally neutral or comfortable were both 1.5 times higher in HW buildings than LW buildings.

To address the first hypothesis, thermal perception and overall comfort were reviewed across all four seasons. Results show that thermal capacity does not seem to have an effect on thermal perception and overall comfort sensation for all four seasons. This insight goes against the first hypothesis that thermal capacity may alleviate discomfort in summer. This unexpected result may be due to the ventilation strategies considered in this study. Thermal mass can have a negative effect of keeping a building warm at night, and therefore thermal mass needs to be combined with night ventilation to dissipate the heat stored during the day (Hacker, 2005). With regard to the second hypothesis, different ventilation types were reviewed. Thermal capacity does not seem to have an effect for MV and PP buildings. However in NV buildings, participants reported to be more thermally neutral and comfortable in HW buildings than in LW buildings. This insight confirms the second hypothesis; a naturally ventilated building, where internal temperature are likely to be less tightly controlled, should have high thermal mass to alleviate potential thermal discomfort. Finally different countries were reviewed. Thermal capacity does not seem to have an effect in oceanic and humid climates. However in Mediterranean climates, participants were more likely to report being thermally neutral in HW buildings. This insight could be particularly useful in the choice of building design as temperatures are set to rise across Europe in near future.

In this study, the thermal capacity of the case-study buildings is identified at an aggregated building level. This is a limitation of the study, as the relationship to be reviewed should be occupants' comfort versus the available heat capacity of the internal surfaces, walls, floors, ceilings and furniture to the occupants are exposed to. This may or may not correspond to the aggregated thermal capacity of the building. Furthermore, the interactions between internal thermal capacity, solar gains and ventilation may be reviewed; in particular where thermal mass is located to best capture solar radiation and to enable convective heat released from materials. Future empirical and modelling studies may review in which building elements is thermal mass most effective in providing a comfortable environment.

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## References

- Arcuri, N., Carpino, C. and De Simone, M. (2016) The role of the thermal mass in nZEB with different energy systems. In proceedings of the *71st Conference of the Italian Thermal Machines Engineering Association*, ATI2016, 14-16 September 2016, Turin, Italy.
- Aste, N., Angelotti, A. and Buzzetti, M. (2009) The influence of the external walls thermal inertia on the energy performance of well insulated buildings. *Energy and Buildings*, 41, pp.1181-1187.
- Hacker, JN, Belcher, SE & Connell, RK (2005). Beating the Heat: keeping UK buildings cool in a warming climate. *UKCIP Briefing Report*. UKCIP, Oxford.
- Holmes, M. and Hacker, J. (2007) Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energy and Buildings*, 39, pp.802-814.
- Humphreys, M.A. and Hancock, M. (2007) Do people like to feel 'neutral'? Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and Buildings*, 39, pp.867-874.
- IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.
- McCartney, K. and Nicol, F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings*, 34(6), pp.623-635.
- Nicol, F. (2001). Smart Controls and Thermal Comfort (SCATs), final report Tasks 3 [Developing an adaptive algorithm]. *Report to the European Commission of the Smart Controls and Thermal Comfort project* (Contract JOE3-CT97-0066), Oxford Brookes University.
- Roucoult, J.-M., Douzane, O. and Langlet, T. (1999) Incorporation of thermal inertia in the aim of installing a natural nighttime ventilation system in buildings. *Energy and Buildings*, 29, pp.129-133.
- Tuohy, P.G. and Humphreys, M.A. and Nicol, F. and Rijal, H.B. and Clarke, J.A. (2009) Occupant behaviour in naturally ventilated and hybrid buildings. *American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Transactions*, 115 (1). pp. 16-27
- Wilson, M., Solomon, J., Wilkins, P., Jacobs, A. and Nicol, F. (2001). Smart Controls and Thermal Comfort (SCATs), final report Tasks 1 [Instrumentation]. *Report to the European Commission of the Smart Controls and Thermal Comfort project* (Contract JOE3-CT97-0066), Oxford Brookes University.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Reliable Methodology to Monitor and Assess Radiant Environments

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**Abstract:** An accurate assessment of thermal comfort allows in-time adjustments in design that leads to achieve a more pleasant indoor or outdoor environment. Among the factors that influence human thermal comfort, Mean Radiant Temperature (MRT) is the focus of the present paper. This work proposes a methodology to facilitate the process of recording, measuring and post-processing of MRT. Current techniques used to estimate MRT in urban environments have several challenges among which accuracy and settling time are the major issues. Moreover, the only output is a single value for MRT without the possibility of sensitivity analysis on effective parameters. The method proposed in this paper, called Radiant Ambience Imaging, is established based on two main techniques: thermography and Numerous Vector (NV) numerical method. The MRT is assessed by capturing infrared and HDR images from a polished hemisphere followed by the numerical analysis. The results not only include the value for the MRT at the point of interest but also the share of each radiant object. The process relies merely on electromagnetic radiation fluxes and there is no need for wind effect corrections. It also provides data post-processing to help architects optimize their designs in order to control MRT in practical applications.

**Keywords:** Mean Radiant Temperature, Thermography, Numerous Vector, Infrared Sphere, Globe Method

### Introduction

Understanding human thermal comfort is an important factor for sustainable architectural design. The goal is to provide, improve and maintain a narrow range of thermal satisfaction for people in built environments. Thermal comfort depends on several parameters related to heat transfer between the human body and the environment, such as clothing, air temperature, air speed, mean radiant temperature, relative humidity. In many cases, designers simply consider rough approximations for the parameters associated with thermal comfort which significantly affects the final outcomes. However, the precision of the calculated value of thermal comfort inevitably hinges on the accuracy of the techniques used to estimate its relating parameters. This has led to the recent advances in the development of more accurate techniques to measure and analyse different parameters such as mean radiant temperature.

Mean radiate temperature (MRT) is a uniform temperature measured at a point subjected to all radiant objects in the surrounding environment (Fanger, et al., 1980; Fanger, et al., 1985; Jones & Chapman, 1994). It is an important index in thermal comfort first

suggested by Korsgaard (1949). MRT depends on view factor, emissivity, and radiation intensity of short-wave and long-wave sources including the Sun, visible sky, and urban surfaces. Considering the complexity of the problem, only few successful numerical methods have been developed to measure MRT, among which RayMan (Matzarakis, et al., 2010), SOLWEIG (Lindberg , et al., 2008), ENVI-met (Bruse, 2009), CityComfort+ (Huang, et al., 2014), and Numerous Vector (NV) method (Hatefnia, et al., 2016) are notable.

On the other hand, experimental techniques have their own limitations; all accepted methods to measure MRT need to apply corrections for wind and ambient temperature. Moreover, they need about 20 to 30 minutes to reach steady-state conditions before recording data. Three common approaches to determine MRT are Black or Grey Globe method, Surface Temperature method, and Infrared Sphere method. In the Black Globe technique, a black spherical globe temperature sensor is used to measure the temperature caused by radiances. The correction for air convection is then made based on the air temperature and velocity measured by an air temperature sensor and an anemometer (Bedford & Warner, 1934). This method requires about 30-minute settling time and is sensitive to the configuration of the sensors (Leung & Ge, 2013). Moreover, it overestimates MRT in presence of direct sunlight (Jones & Chapman, 1994) and does not account for radiant asymmetry. In the Surface Temperature method, temperature sensors are mounted on surrounding surfaces to measure their temperatures which along with their view factors yield the MRT at the point of interest. This method needs significantly longer preparation time than the Black Globe method and considers many approximations to calculate view factors. Moreover, the measured temperature may not represent the actual surface temperature in case of a complex temperature gradient. The Infrared Sphere method (Leung & Ge, 2013) is based on Nusselt Analog approach and uses a sphere of highly polished low-emissivity reflector and two reversed-facing temperature sensors to measure the average surface temperature. Surface temperatures and their view factors are determined using the sensors. Leung and Ge (2013) used a sphere made of stainless steel which is not the best reflective material. Their method excludes shortwave radiations, but need no settling time. It proved to be more accurate than the other methods although the measurement of MRT with only two infrared sensors is still a rough approximation of all radiations.

This paper introduces a new approach to measure MRT. The method is similar to the Infrared Sphere method to some extent, but has several advantages. It combines the infrared sphere method and the numerical NV method to calculate MRT without using any temperature sensors or anemometers. Furthermore, it makes it possible to record and analyse the effect of surrounding objects on the MRT. The method is discussed in the next section followed by several examples to prove its capabilities.

## Methodology

The method proposed in this paper to measure MRT is named Radiant Ambience Imaging (RAI). It is an experimental imaging of thermal radiations at a desired point followed by a numerical data processing. New technology has made thermography easier and more precise. On the other hand, the development of powerful computational methods accelerates the numerical analyses. The experimental setup consists of a metallic hemisphere of low emissivity that is fixed exactly 1.1 m above the ground corresponding to the average height of the centre of gravity for adults (Mayer & Höppe , 1987). A camera is placed 0.5 m above the hemisphere. The setup is shown in Figure 1(a). The results are validated by a comparison

with the temperature measured by the Black Globe method using Kestrel 5400 Heat Stress Tracker shown in Figure 1(b). After the images are captured at the given time, the data are numerically processed to obtain the view factors and consequently the MRT at the point of interest. In general, MRT can be calculated using the following equation:

$$T_{mrt} = \sqrt[4]{(S_{str}/(\varepsilon_p\sigma))} - 273.15 \quad \text{in } ^\circ\text{C} \quad (1)$$

where  $\sigma$  is the Stefan-Boltzmann constant equal to  $5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^4$ ,  $\varepsilon_p$  is the emissivity of the human body with standard value of 0.97, and  $S_{str}$  is the mean radiant flux density of the human body, which depends on the short-wave and longwave radiant fluxes as shown below (VDI, 1994) :

$$S_{str} = \alpha_k \sum_{i=1}^n K_i F_i + \varepsilon_p \sum_{i=1}^n L_i F_i \quad (2)$$

where  $\alpha_k$  is the absorption coefficient for short-wave radiation with standard value of 0.7,  $K_i$  and  $L_i$  are respectively the short-wave and long-wave radiation fluxes of radiant surface  $i$  in  $\text{W/m}^2$ ,  $F_i$  is the view factor of surface  $i$  with respect to the reference point, and  $n$  is the number of surrounding surfaces.



Figure 1. The experimental setup: (a) the hemisphere and DSLR camera, (b) Kestrel 5400 Heat Stress Tracker.

The Numerous Vector method (Hatefnia, et al., 2016) is the numerical technique used to process the images. The procedure is as follows: a unit sphere is placed at the point of interest, which is also the centre of the hemisphere.  $N$  number of points are homogeneously distributed on the sphere. The fraction of points inside each surface on the sphere yields the view factor of that surface with respect to the point of interest. Moreover, the value of radiation fluxes can be easily recorded at each point on the sphere by using the IR and HDR images. In fact, for this particular application of the NV method, there is no need to separately find the view factors and radiation fluxes for each surface to find  $S_{str}$  in Eq. (2). If enough number of points is distributed on the sphere, it would be computationally more efficient to assume a constant flux on a small surface that each point centred and therefore, assign a flux value to each point. Subsequently,  $K_i F_i$  and  $L_i F_i$  are calculated for each point  $i$  and then  $S_{str}$  can be obtained.

One beneficial feature that the application of the NV method adds to the Radiant Ambience Imaging technique is the possibility to analyse the effect of individual surfaces on

the MRT. This can be accomplished by assigning the points on the sphere to the surrounding surfaces. If there are  $n_s$  points inside the projected surface of a surrounding object on the sphere, the view factor of that surface is  $F_s = n_s/N$ . Since the view factors of each of the  $N$  vectors is  $F_i = 1/N$ , the fluxes of the surface based on the ones of the vectors are  $K_s = K_i/n_s$  and  $L_s = L_i/n_s$ , which are the average values. By knowing the radiant fluxes of each surface, the designer can study the effect of the surrounding surfaces to monitor and control the MRT. More details on the NV method can be found in the paper published by Hatefnia et al. (2016). In general, two different images are needed to calculate MRT: one is an infrared picture to capture longwave radiations and the other one is high-dynamic-range (HDR) to obtain shortwave radiations from the surrounding objects. The HDR image is the result of processing several standard images to illustrate actual distribution range of luminosity within the photographed scene. An HDR image can be created from a series of exposure-bracketed images using a standard digital or analogue camera by the technique pioneered byDebevec and Malik (1997), although this is not as accurate as using a calibrated CCD camera. The conversion of luminance value to radiance for each point is performed based on the luminous efficacy of the light visible in that point, which depends on the colour scheme of the space. The details of estimating luminous efficacy can be found in the paper published by Inanici et al. (2015). However, to accurately determine the relative response of the CCD sensor for each wavelength the IR-cut filter of the DSLR camera is removed. This allows the near infrared (NIR) waves to be recorded and extends the spectrum to 1000-1100 nm. The RGB colours of the HDR photo shows the dominant wavelengths. The RGB codes from each pixel then are converted to HSV (hue, saturation, and value) to be matched by the light spectrum after calibration to determine the wavelengths. A series of Python codes is used to run the aforementioned process and map the environmental radiance on each pixel. The images are fused into an HDR image using the software called Photosphere (Ward, 2005). Figure 2 shows as example of IR and HDR imaging and the resulting nodal radiation fluxes after applying the NV method.

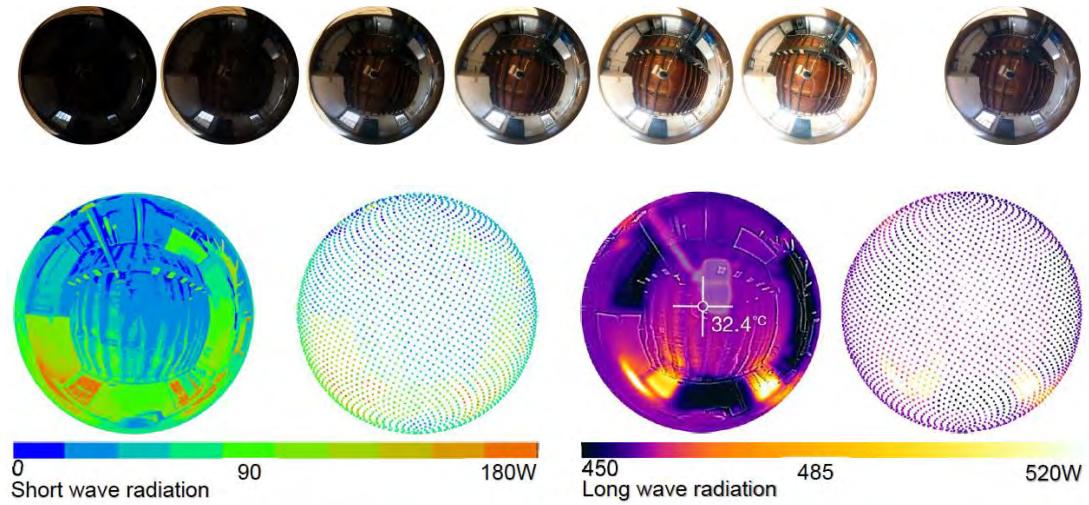


Figure 2. HDR imaging and the corresponding shortwave and longwave radiation fluxes.

One should note that the image taken by the camera placed straight on top of the hemisphere would not capture a picture of the whole hemisphere. In spite of this, the field of view in the image can cover more than what is above the horizon line. This is shown in Figure 3 for a hemisphere of radius  $r$  whose centre is distanced  $h$  from the camera. The red circle is

the total field of view while the green circle is the horizon line. The field of view of the camera depends on distance  $h$  as illustrated; the farther the camera from the hemisphere, the larger is the field of view which results capturing more surfaces. As  $h$  increases, it might be needed to zoom in to get a satisfactory image. The radiant flux of the part of the ground that is not captured in the IR or HDR image is approximated by the outermost points on the sphere captured in the image.

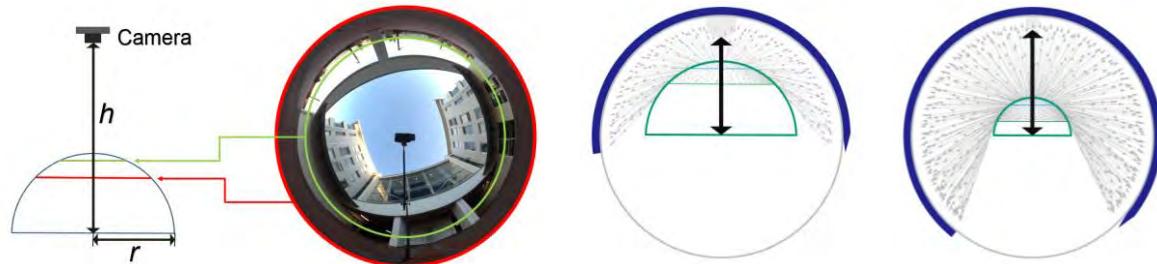


Figure 3. The field of view of the camera placed straight on top the hemisphere.

Another advantage of the Radiant Ambience Imaging method is that MRT can be measured at each point of interest with only two IR and HDR images. There is no need to record air temperature or air velocity to perform a heat transfer analysis for any corrections. Moreover, no settling time is needed to reach steady-state conditions. The results of the application of the proposed method for several cases are discussed in detail in the following section.

## Results and Discussion

In this section, the capabilities of the Radiant Ambience Imaging method are demonstrated in indoor and outdoor environments. The IR camera used is FLIR One which captures long-IR radiations of 8 to 15  $\mu\text{m}$ . This is the bandwidth of the heat emitted by radiation from surrounding objects. A polished silver hemisphere is used because of the very low emissivity (about 0.03) for vast range of wavelengths so that it reflects almost all the environmental radiations. The number of points used in the NV method for all the examples are 10,000 points which found to yield accurate results as even the smallest surrounding surfaces are hit on the sphere and considered in the calculations. Two of the case studies are indoor spaces with different intensities of sunlight exposure and the last one is an outdoor environment with direct solar radiation.

### ***Case Study 1: Indoor space with limited sunlight***

The setup in Figure 1 is placed in the center of a  $6\text{m} \times 6\text{m}$  meeting room with two closed windows. The direct solar radiation is on the floor and partly on wall. The results are shown in Figure. 4. As it can be seen in the HDR picture, the wooden ceiling, walls and windows and most part of the floor are captured by the camera. The surface temperatures vary between 29°C on the shaded walls and 41°C on a small area close to the windows. The Radiant Ambience Imaging method measures a the total of 16.73  $\text{W/m}^2$  of shortwave radiant flux density and 455.76  $\text{W/m}^2$  longwave radiant flux density at the center of the room. This shows the significant impact of longwave radiations in interior spaces without direct solar radiations

on point of interest. The combined mean radiant flux density,  $S_{str}$ , is 472.49 W/m<sup>2</sup> which results in a mean radiant temperature of 31.29°C. The MRT measured by a black globe is 29.4°C. This shows a 6.4% difference between the two methods.

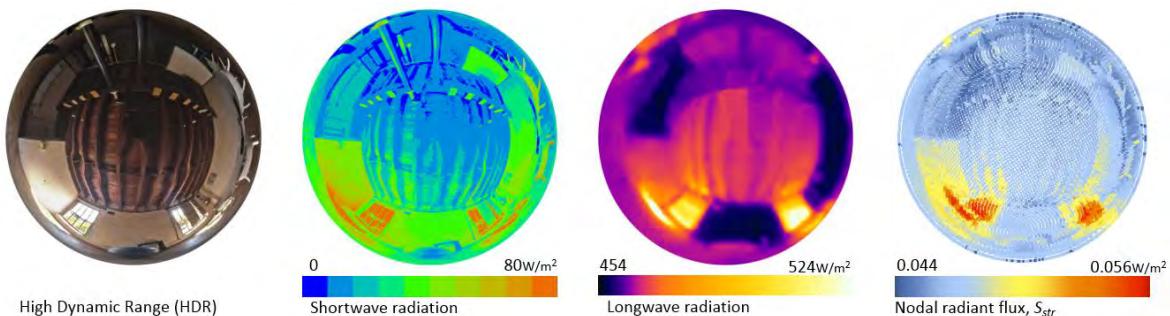


Figure 4. The results of the RAI method for an indoor space with limited sunlight.

### **Case Study 2: Indoor space with diffuse sky radiation**

In this example, the point of interest is an office desk close to an open window subjected to diffuse sky radiation. The results of the RAI method are shown in Figure 5. The surface temperatures vary between 22°C on the shaded walls and 35°C on some surfaces such as the computer monitor, ceiling and outdoor surfaces. The total  $S_{str}$  is 459.47 W/m<sup>2</sup> of which 43.70 W/m<sup>2</sup> is the shortwave flux and 415.77 W/m<sup>2</sup> is the longwave flux. Similar to the previous example, the MTR is mostly affected by the longwave radiations of the surrounding objects in interior spaces. In this example, the diffuse sky radiation has about 10% weight in the total  $S_{str}$ . Subsequently, the calculated mean radiant temperature is 29.17°C while the black globe's temperature is 27.4°C which shows a 6.4% difference.

In this example, the radiations from the window and the roof are found to have important roles on the MRT of the point of interest. These surfaces are selected for the post-processing analysis. The total mean radiant flux density of the window is measured to be 32.26 W/m<sup>2</sup> (7.14 W/m<sup>2</sup> shortwave flux and 25.12 W/m<sup>2</sup> longwave flux) at the point of interest while that of ceiling is 53.04 W/m<sup>2</sup> (4.67 W/m<sup>2</sup> shortwave flux and 48.36 W/m<sup>2</sup> longwave flux). Therefore, the weights of the window and ceiling in the total  $S_{str}$  are 7% and 11.5%, respectively. By modifying the view factors (shape and orientation) of such surfaces, the MRT at any point can be improved to the desired range.

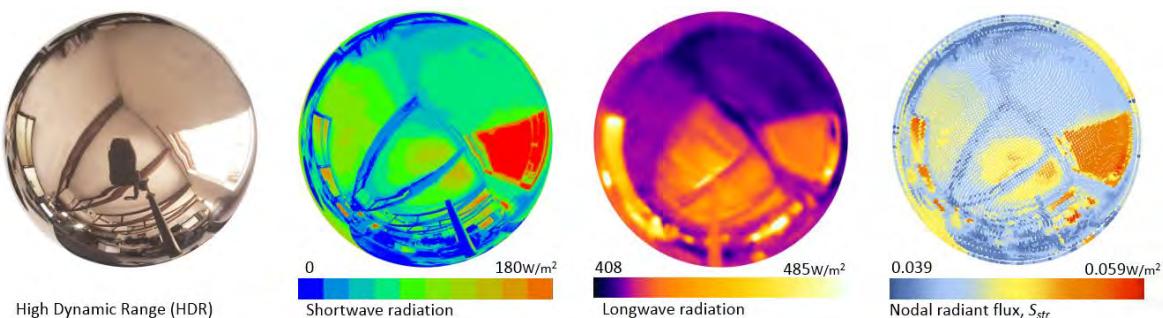


Figure 5. The results of the RAI method for an indoor space with diffuse sky radiation.

### **Case Study 3: Outdoor environment with direct solar radiation**

The MRT in an outdoor space on a balcony with direct solar radiation is measured by the application of the RAI method. The images are seen in Figure 6. The IR image shows the temperatures vary between -25°C for the sky and 99°C for the Sun. In this example, the total  $S_{str}$  is measured to be 693.89 W/m<sup>2</sup> of which 300.18 W/m<sup>2</sup> is the shortwave flux and 393.72 W/m<sup>2</sup> is the longwave flux. This shows the high impact of the direct solar radiation on the point of interest. The calculated mean radiant temperature is 61.99°C while that of the black globe is 62.15°C. The percent error is 0.26% and negligible. In the post-processing analysis, the total shortwave and longwave fluxes from different directions are also illustrated in Figure 6. By obtaining such graphs, the RAI method allows the designers to assess and control asymmetric discomfort. This feature is unique to this method.

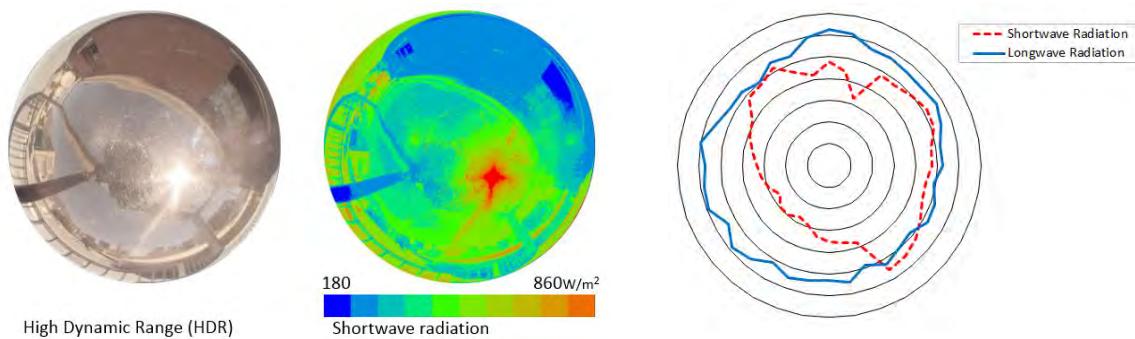


Figure 6. The results of the RAI method for an outdoor space with direct solar radiation.

## **Conclusions**

The new Radiant Ambience Imaging method is proposed in this paper to assess the mean radiant temperature of indoor and outdoor environments. The method consists of a setup to take IR and HDR images from a polished hemisphere followed by a numerical analysis using the Numerous Vector method. The RAI method is proved to be accurate and more capable compared to other available techniques. By the application of this method, not only the MRT and shortwave and longwave fluxes are measured at the point of interest, the post-processing analysis provides a lot of valuable information such as the share of each surface in the total heat flux, sunlight effect, MRT control, and asymmetric discomfort. Moreover, the RAI method does not need a settling time to reach steady-state conditions or any temperature sensors. The method is reliable even in the presence of direct sunlight or surfaces with complex temperature gradients. It merely needs two IR and HDR images of the surrounding environment and there is no need to apply corrections for wind effects. Furthermore, the view factors are incorporated in the calculations without dealing with complicated equations for different geometries. The Radiant Ambience Imaging method provides an effective tool for designers to measure, control, and monitor the mean radiant temperature of any point in indoor or outdoor built environments.

## References

- Bedford, T. & Warner, C., 1934. The globe thermometer in studies of heating and ventilation. *Journal of the Institution Of Heating And Ventilating*, 7(21), p. 544.
- Bruse, M., 2009. *ENVI-met V3.1 – A three dimensional microclimate model..* s.l.: Ruhr University at Bochum, Geographischer Institute, Geomatik.
- Debevec, P. E. & Malik, J., 1997. Recovering High Dynamic Range Radiance Maps from Photographs. *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, pp. 369-378.
- Fanger, P., Banhidi, L., Olesen, B. & Langkil, G., 1980. Comfort limits for heated ceilings. *ASHRAE Transactions*, 86(2), pp. 141-156.
- Fanger, P., Ipsen, B., Langkilde, G. & Olese, B., 1985. Comfort limits for asymmetric thermal radiation. *Energy and Buildings*, Volume 1, pp. 225-236.
- Hatefnia, N., Barakati, A., Ghobad, M. & Eslam Panah, A., 2016. *A Novel Methodology to Assess Mean Radiant Temperature in Complex Outdoor Spaces*. s.l., s.n.
- Huang, J., Cedeño-Laurent, J. G. & Spengler, J. D., 2014. CityComfort+: A simulation-based method for predicting mean radiant temperature in dense urban areas. *Building and Environment*, October, Volume 80, pp. 84-95.
- Inanici , M., Brennan, M. & Clark, E., 2015. Spectral Daylighting Simulations: Computing Circadian Light. *Proceedings of BS2015:the 14th Conference of International Building Performance Simulation Association*, Dec. pp. 7-9.
- Jones, B. & Chapman, K., 1994. *Simplified method to factor mean radiant temperature (MRT) into building and HVAC system design. Final Report of ASHRAE Research Project 657*, Atlanta: ASHRAE.
- Korsgaard, V., 1949. Necessity of using a directional mean radiant temperature. Heating, Piping and Air. *Copenhagen: ASME Journal Section*, pp. 117-120.
- Leung, C. & Ge, H., 2013. An infrared sphere method to measure mean radiant temperature.. *ASHRAE Transactions*, Volume 119, Part 1.
- Lindberg , F., Holmer , B. & Thorsson , S., 2008. SOLWEIG 1.0—Modeling Spatial Variations of 3D Radiant Fluxes and Mean Radiant Temperature in Complex Urban Settings. *International Journal of Biometeorology*, Volume 52(7), pp. 697-713.
- Matzarakis, A., Rutz, F. & Mayer, H., 2010. Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International Journal of Biometeorology*, March, 54(2), p. 131–139.
- Mayer, H. & Höppe , P., 1987. Thermal comfort of man in different urban environments. *Theoretical and applied climatology*, 38(1), pp. 43-49.
- VDI, 1994. *Environmental meteorology, interactions between atmosphere and surface; calculation of short-and long wave radiation.*, Düsseldorf: Handbuch Reinhaltung der Luft, Band 1b.
- Ward, G., 2005. *Anywhere Software*. [Online] Available at: <http://www.anyhere.com/> [Accessed 25 June 2005].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Perceived importance of indoor environmental factors in different contexts

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**Abstract:** How the indoor environment is evaluated by an individual is influenced by many factors, i.e. a person's state (physiological, psychological), the social and the built environment. These form a person's evaluation system of the indoor environment. Among further factors, the evaluation system comprises the importance of indoor environment factors. The aim of this paper is to explore context driven differences in the importance rating of indoor environment factors. Data from a survey collected among different groups of students ( $n = 300$ , temperate and tropical climate, 2006 - 2016) are compared with survey results from the German ProKlimA-Study ( $n = 4596$ ). In both studies, the same questionnaire was used. The impact of sex, age, background and climatic zone is analysed. The results suggest differences in the importance caused by these factors. Because of the limited number of respondents and the consideration of only two climate zones, further research is required to identify different priorities towards indoor environment factors in different contexts. The results could support future context-specific design guidelines for indoor environments.

**Keywords:** expectation, psychological state, evaluation, individual experience, acclimatisation, climatic imprint

### Introduction

How the indoor environment is evaluated by an individual is influenced by many factors, i.e. a person's state (physiological, psychological), the social and the built environment. These form a person's evaluation system of the indoor environment. Among further factors, the evaluation system comprises the importance of indoor environment factors a person attaches to these factors (Hellwig, 2015). The importance of indoor environment factors to persons can be interpreted as the expectation of persons towards these factors (Bischof et al. 2007). In the ProKlimA study Bischof et al. (2003, p. 106-107) found that office workers with Sick Building Syndrome (SBS) symptoms rated the importance of indoor environment factors higher than office workers showing no SBS symptoms. In mechanically ventilated offices of the ProKlimA study, phase I, more respondents voted 'extremely important' for air humidity, ventilation, room temperature and air movement compared to naturally ventilated offices (Hellwig, 2005). Based on the data of phase II, Bischof et al. (2007) analysed the extra-physical impacts on room temperature importance and found female sex, young age, air-conditioning and bad job evaluation increasing the chance to rate the room temperature 'extremely important'. Lai and Yik (2007) investigated the perceived importance thermal comfort, air cleanliness, odour and noise have for users of a building in Hong Kong. They found differences with regard to gender, between workers or visitors and the duration of their stay.

Post occupancy evaluations survey ratings or votes expressing the degree of satisfaction with the indoor environment. Hereby, a person's satisfaction or dissatisfaction

with a certain factor does outweigh other factors if this factor is important to the person. If a person is dissatisfied and regards the factor of interest as extremely important there was a need for action or change. Importance ratings allow to weight satisfaction votes and are used in so called action relevance matrices in market research but also in post occupancy evaluation (e.g. Wagner et al., 2007).

The hypothesis in this paper is that context or previous experience have an impact on the importance rating of indoor environment factors. The aim of this paper is to explore differences in the importance rating of indoor environment factors driven by sex, age, education progress and climatic zone.

## Materials and Methods

The questionnaire used in this study is very short. It asks for the actual date, age, sex, study field and the importance of indoor environment factors. The latter part was taken from a questionnaire already applied in the German ProKlimA study (Bischof et al. 2003). The subjective importance of seven different factors of the indoor environment, listed here in the order of their appearance on the questionnaire: lighting, air humidity, ventilation, room temperature, sound level, air movement, odours is rated with the questionnaire. The five-point ordinal scale of importance ranges from 'not important', 'slightly important', 'moderately important', 'very important' to 'extremely important'.

Since 2006 I have been teaching courses on indoor climate, partly coupled with foundations of building physics or energy balance calculations within different study programmes on the Master's level in Bavaria, Germany and in Malaysia and Singapore. One important teaching goal is to raise understanding of the diversity of people and their diverse perception and preferences, to develop an understanding that each individual evaluation system is a result of the external environment conditions (i.e. climate), the internal built environment (e.g. room type and configuration) and the social environment (e.g. norms, habits). Each lecture series on indoor climate starts with the distribution of the questionnaire on the importance of indoor environment factors. In one of the later lectures a group of students does a simple analysis of the data. All courses have been taught for students studying in the building sector. A majority of students had a study focus on energy efficiency in buildings or sustainable design.

The data used in this paper comprise data from the ProKlimA study (Bischof et al. 2003) and my own data collected during my lectures between 2006 and 2016. Table 1 shows a summary of the main information on the data sets used in this paper. The ProKlimA study, phase I, comprises responses of 4596 office workers (56% female, 44% male) in 14 different German office buildings which were collected in different areas of Germany, climatic zone Dfb & Cfb according to Köppen-Geiger classification.

My own data comprise data from one undergraduate student group of the first semester of study field 'E' (age: min-median-max: 19-22-23, sex: male/female: 47/53%), three graduate student groups of study field 'B' (age: 21-24-28, m/f: 76/24%), and seven graduate student groups of study field 'E' (age: 21-25-48. m/f: 53/47%). All these students have been studying in Bavaria, Germany (between Dfb & Cfb). The data of these groups were collected in different years, always in the winter term, i.e. between October and December. The graduate students had different backgrounds from their undergraduate studies: architecture, civil engineering, building services, or other fields of engineering or study field 'E'. Furthermore, my own data also comprise two small graduate student groups of study field 'G' in Malaysia (age 24-26-39, m/f: 60/40%). All students were from Malaysia

(tropical rainforest climate, Af) despite one student who was from a country with tropical monsoon climate (Am) and another student from arid climate (BWh, BSh or BSk). Their data are part of the data set as they could not be identified from the questionnaire and therefore were not excluded. More data were collected among two graduate student groups studying field 'S' in Singapore (age: 23-26-44, m/f: 39/61%). Most of the students were from different parts of India comprising subtropical and tropical climates (Cwa, Cwb, Af, Am, Aw, BSh), furthermore students from other parts of tropical South-East Asia (Af, Am), subtropical China (Cfa), and one from Columbia (Cfb). While studying, all students were living under tropical rainforest climate (Af) conditions of Singapore.

At the time when the questionnaire was distributed to the undergraduate students (1<sup>st</sup> semester) only two third of the lessons in foundations in building physics were provided. Indoor climate is not part of the syllabus of this or other modules of the 1<sup>st</sup> semester. To all graduate level students in all three countries, the questionnaire was distributed in the beginning of the first lesson of the indoor climate lecture series within the course.

Table 1. Overview on the data used in this paper. The study field is encoded. \*See acknowledgement.

Study/ Data Source	Year/ period of data collection	Group type	Country	Number of respondents
ProKlimA study/ Bischof et al. 2003	1995-1998, different seasons	Office Workers	Germany	4596
Own data	Dec 2013	Students*, undergraduate level, 1 <sup>st</sup> semester, study field 'E'	Germany, Bavaria	47
Own data	2006/ 2007/ 2008, all October	Students*, graduate level, study field 'B'	Germany, Bavaria	14/ 21/ 15
Own data	Oct 2008/ Oct 2009/ Nov 2010/ Nov 2012/ Oct 2013/ Oct 2014*/ Oct 2016	Students*, graduate level, study field 'E'	Germany, Bavaria	18/ 13/ 22/ 18/ 11/ 27/ 34
Own data	Sept 2013/ May 2014	Students*, graduate level, study field 'G'	Malaysia	13/ 12
Own data	Sept 2014/ Aug 2015	Students*, graduate level, study field 'S'	Singapore	16/ 19

In this paper data from the ProKlimA study (Bischof et al. 2003, Hellwig, 2005) are used to investigate whether it is possible to detect differences in importance rating depending on sex or age group. Data of student groups were used in order to investigate difference according to the study progress of students in the same study field 'E' and to show differences between student groups of similar age but with different climatic background. Data from the 'young' age group of the ProKlimA study are compared with the graduate student group of Germany, presuming that these groups incorporate different experiences (studying vs office work).

The data analysis uses cumulated relative frequencies of the two categories of importance: 'very important' and 'extremely important', the rank sum and the rank of the rank sum. Rank sum is the sum of the individual ranks of each environment factor. The ranks of the indoor environment factors were determined using the rank sum. Sorted bubble charts showing the ranking of the indoor environment factors according to rank sum and the relative frequencies of responses in the five categories of importance for each environment factor. Differences in the environment factor ranks within each sample were tested with the Friedman test; pairwise differences between the factors were tested with the

Wilcoxon and Wilcox test procedure (Hedderich and Sachs, 2012, p. 562-570). Both tests were carried out on  $p = 0.05$  level, two sided. Calculations were processed with Excel. Radar charts are used in order to display the different ranking patterns of importance. Normalised rank sums are used. The factor with the highest importance (lowest rank sum) is displayed with "100" and the factor having the lowest importance (highest rank sum) is displayed with "0". In the radar charts the factors appear according to their order of appearance on the questionnaire in clockwise direction.

## Results

Table 2 provides an overview on the results. The results of the Friedman and Wilcoxon-Wilcox tests are given in the last column. For all groups, rank differences are significant (Friedman test,  $p = 0.05$  level).

Table 2. *Cumulated relative frequencies of 'extremely important' and 'very important'*, rank sum and **rank of rank sum** for each analysed sample or subsample. The number of complete responses is given in brackets in the first column. Results of the Friedman test and Wilcoxon-Wilcox test are given in the last column.

Group name	Lighting	Air humidity	Ventilation	Room temperature	Sound level	Air movement	Odours	Friedm. n Wil.-Wil. <sup>1)</sup>
ProKlimA, women (N = 2379)	67 8924 <b>3</b>	59 9714 <b>4</b>	77 7592 <b>1</b>	70 8474 <b>2</b>	57 9851 <b>5</b>	45 11396 <b>7</b>	51 10662 <b>6</b>	* 20
ProKlimA, men (N = 1952)	63 7083 <b>2</b>	49 8319 <b>5</b>	69 6408 <b>1</b>	57.1 7439 <b>4</b>	57.4 7251 <b>3</b>	36 9421 <b>7</b>	43 8737 <b>6</b>	* 18
ProKlimA, young (N = 1141)	65 4254 <b>3</b>	56 4729 <b>4</b>	78 3429 <b>1</b>	71 3887 <b>2</b>	51 4877 <b>5</b>	43 5482 <b>7</b>	45 5292 <b>6</b>	* 19
ProKlimA, not young (N = 3188)	66 11736 <b>2</b>	54 13299 <b>5</b>	72 10566 <b>1</b>	62 12010 <b>3</b>	59 12227 <b>4</b>	41 15327 <b>7</b>	48 14100 <b>6</b>	* 18
undergraduate, field 'E' (N = 47)	77 154 <b>4</b>	13 268 <b>6</b>	64 165 <b>5</b>	74 152 <b>2.5</b>	68 152 <b>2.5</b>	17 275 <b>7</b>	77 151 <b>1</b>	* 10
graduate, field 'E' (N = 139)	63 517 <b>3</b>	39 675 <b>7</b>	78 445 <b>1</b>	66 496 <b>2</b>	53 566 <b>5</b>	38 665 <b>6</b>	61 530 <b>4</b>	* 10
graduate, field 'B' (N = 50)	58 189 <b>3</b>	34 241 <b>6</b>	62 178 <b>2</b>	76 150 <b>1</b>	48 210 <b>5</b>	36 244 <b>7</b>	54 190 <b>4</b>	* 2
graduate, field 'G' (N = 25)	68 112 <b>5</b>	72 117 <b>6</b>	92 67 <b>1</b>	92 69 <b>2</b>	32 143 <b>7</b>	92 96 <b>3</b>	68 98 <b>4</b>	* 3
graduate, field 'S' (N = 33)	82 133 <b>4</b>	59 150 <b>6</b>	100 71 <b>1</b>	76 132 <b>3</b>	38 179 <b>7</b>	85 126 <b>2</b>	74 135 <b>5</b>	*

<sup>1)</sup>\* Friedman: \* differences in ranks within group are significant ( $p=0.05$  level), Wil.-Wil.: Wilcoxon-Wilcox: overall 21 pairwise differences exist per group, n is the number of significant pairwise differences ( $p=0.05$  level).

### Women vs. men (ProKlimA)

Women responded more often (+4 to +13 percent point) with 'extremely' and 'very important' compared to men, except for sound level which shows the same frequencies for

both men and women (Table 2). This can also be seen from Figure 1a) and b). For both, women and men, ventilation is the most important factor. Least important are odour and air movement. For women, room temperature is the second important. Although we can see the same respondent's rate in the categories 'extremely' or 'very important' for sound level, for men this factor ranks 3<sup>rd</sup> compared to women on the 5<sup>th</sup> rank. For the women group 20 out of 21 pairwise rank differences are significant. Only the difference between the rank of sound level and air humidity is not significant. For the men group all pairwise differences are significant except the rank differences between lighting, sound level and room temperature. The importance pattern displayed in Figure 2a) show a rather similar pattern for women and men despite the higher relative importance of sound level for men.

#### ***Young vs. not young (ProKlimA)***

About ¼ of the respondents in the ProKlimA study was younger than 31. The cumulated frequencies of the 'extremely' or 'very important' categories are very similar to those for the women group except -6 percent point lower frequencies for sound level and odours. Ranks are the same. Also the importance pattern (Figure 2b)) is very similar. Frequencies for the not young group are generally lower compared to the young group except for sound level (+8 percent points) and odours (+3 percent points). The ranks are almost the same when compared to the male group and when considering that pairwise rank differences between lighting, room temperature and sound level are not significant. A cross tabulation unveils that of 4503 respondents only 7% are male and younger than 31.

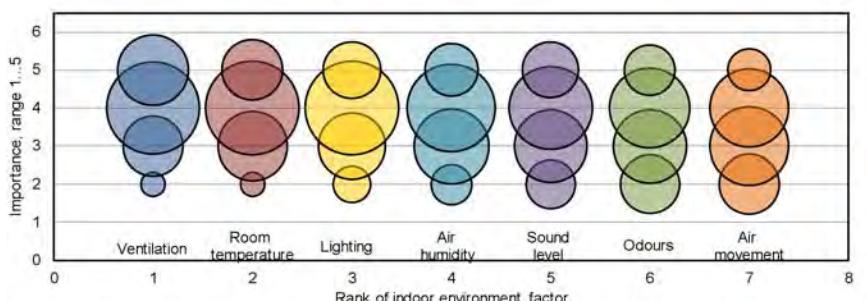
#### ***Undergraduate vs graduate students and graduate students vs young (ProKlimA)***

Cumulated frequencies of the undergraduate students show the remarkable result that only 13 to 17% voted for air movement and air humidity being 'extremely' or 'very important'. For the other factors they voted rather similar and did not put a preference on any factor. 10 out of 21 pairwise differences are significant characterising the difference between air movement and air humidity on one side and the other factors on the other side. There is a similar characteristic in the importance patterns of the undergraduate and the graduate although there is a different magnitude of importance. Figure 1c) shows the distribution of the response pattern for the merged two samples of German graduates. For the graduates odour appears to be much more important compared to the young office workers (Figure 2d)). For the latter air humidity plays an important role. The difference between the two samples is the education background as the students attended lessons on building physics, ventilation systems or lighting (at the time of the questionnaire not on indoor climate). Another main difference is the time period of data collection: between the surveys lay 10 to 20 years.

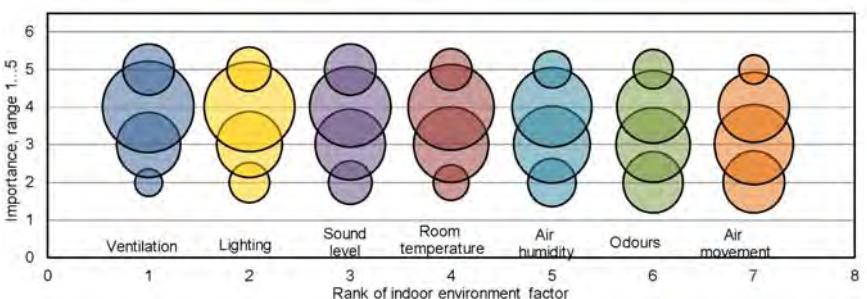
#### ***Different climates***

Figure 1d) displays the distribution of the responses of the graduate students origin from tropical rainforest climate. Figure 1e) shows the same of the students studying in tropical rainforest climate with tropical or subtropical climatic background. For both groups ventilation is the most important factor. Compared to all other groups, air movement is much more important to these two groups. Sound level appears being less important.

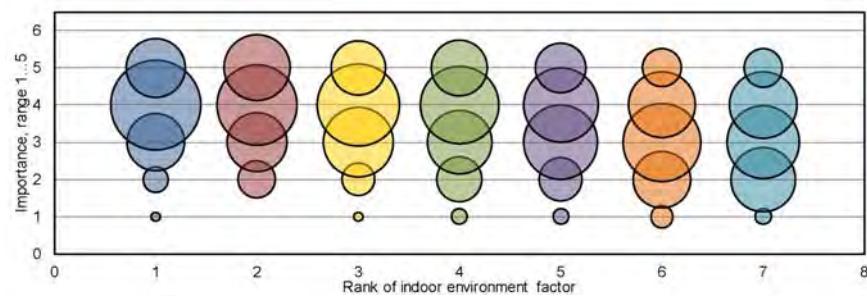
- a) Women  
all pairwise rank differences are significant except ranks 4-5



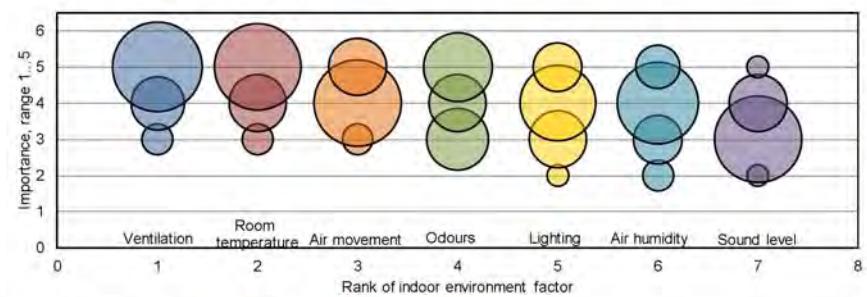
- b) Men  
all pairwise rank differences are significant except ranks 2-3, 2-4 and 3-4



- c) Graduate students, study field 'E' and 'B'  
pairwise rank differences are not significant between ranks 1-2, 1-3, 1-4, 2-3, 2-4, 3-4, 3-5, 4-5 and 6-7,



- d) Graduate students, study field 'G'  
pairwise rank differences are significant between ranks 1-6, 1-7 and 2-7



- e) Graduate students, study field 'S'  
pairwise rank differences are significant between ranks 1-3, 1-4, 1-5, 1-6, 1-7

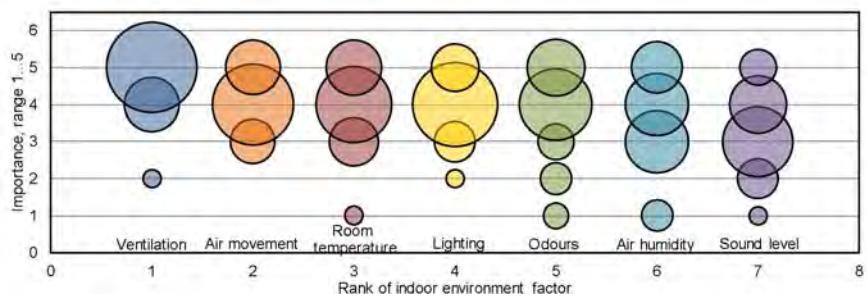


Figure 1. Bubble charts sorted by rank sum of environment factor a) women ( $N = 2379$ ), b) men ( $N = 1952$ ); a to b) all data: ProKlimA (Bischof et al. 2003); c) temperate climate, graduate students, study field 'E' and 'B' ( $N = 189$ ), d) tropical rainforest climate, graduate students, study field 'G' ( $N = 25$ ); e) mainly tropical to subtropical climate, studying in tropical rainforest climate, graduate students, study field 'S' ( $N = 34$ ); c to e) own data.

Although these students have been living under all year round high relative humidity this factor seems less important to them. The importance pattern of both groups is rather similar except the higher importance to room temperature given by the graduates originating from and living in tropical rainforest climate (Figure 2e)). The pattern of the

merged tropical group differs from the pattern of the German temperate climate students in the importance of air movement, sound level and air humidity.

## **Discussion & conclusion**

The aim of this paper was to explore differences in the importance of indoor environment factors depending on sex, age, education progress and climatic zone. Hereby, sex, age, level of education and climate could stand for a certain experience. Age, sex and climate could also stand for a general sensitivity or for learnt sensitivity because of previous negative experience. Age could also be seen as an identifier for changes in social norms and expectations. Education factor (progress in own studies) could show how a study specific focus could have an impact on the evaluation system. Climatic experience and/or societal specific habits or norms could also result in different importance evaluation. Lai & Yik (2007) found for both male and female users that odour has the greatest importance to them. This is different from the sample of the German ProKlimA (1995-1998) study but for the students from Germany (2006-2016) odour seems to be more important. Noise was found being more important to male users than female users in Lai & Yik's study. This is consistent with the finding from the ProKlimA study although the majority of male office workers were in the 'not young' group. So age could be the reason for the higher importance of sound level. The undergraduate students reported no specific preference; for 5 out of 7 factors they assigned high importance. Since these students were in their 1<sup>st</sup> semester while responding to the questionnaire, they could be regarded as the most naïve sample with respect to knowledge on indoor environment.

The results presented here serve as a pilot study with a low number of subjects in the students groups. Despite the small sample size and the lack of fully significant pairwise test results tendencies are already visible. The methodology applied here to detect, assess the magnitude of the differences between the ranks and visualise the importance patterns which were applied in this paper seems to be applicable also for extended data samples. The results could support future context-specific design guidelines for indoor environments.

## **Acknowledgement**

I would like to thank my students for supporting the data collection and providing useful insights in their importance rating. Many thanks also to my colleague, Dr. I. Heusler who carried out the data collection in autumn 2014 in Germany while I was abroad.

## **References**

- Bischof W., Bullinger-Naber M., Kruppa B., Schwab R., Müller B.H. (2003): Expositionen und gesundheitliche Beeinträchtigungen in Bürogebäuden – Ergebnisse des ProKlimA-Projektes. (Expositions and impairments of health in office buildings – Results of the ProKlima-project) Fraunhofer IRB Verlag, Stuttgart. ISBN: 3816764088
- Bischof, W.; Hellwig, R.T.; Brasche, S. (2007): Thermischer Komfort - die extraphysikalischen Aspekte (Extraphysical parameters of thermal comfort). *Bauphysik* 29, No. 3, pp. 208-212. DOI: 10.1002/bap.200710029
- Hellwig, R.T. (2005). Thermische Behaglichkeit - Unterschiede zwischen frei und mechanisch belüfteten Gebäuden aus Nutzersicht (Thermal comfort - Natural ventilation versus air-conditioning in office buildings from the occupant's point of view). In German language. PhD, Munich University of Technology, Germany.
- Hellwig R.T. (2015). Perceived control in indoor environments: a conceptual approach. *Building Research & Information*, 43(3), pp. 302-315. DOI: 10.1080/09613218.2015.1004150
- Hedderich, J.; Sachs, L. (2012): Angewandte Statistik. Methodensammlung mit R, 14. Ed. Springer Heidelberg Dordrecht London New York ISBN: 978-3-642-24400-1

Lai, J.H.K.; Yik, F.W.H. (2007) Perceived importance of the quality of the indoor environment in commercial buildings. *Indoor and Built Environment*, 16,4, pp 311-321. DOI: 10.1177/1420326X07080463

Wagner, A.; Gossauer, E.; Moosman, C.; Gropp, Th.; Leonhardt, R. (2007): Thermal comfort and workplace occupant satisfaction – results of field studies in German low energy office buildings. *Energy and Buildings*, 39, pp. 758-769. DOI: 10.1016/j.enbuild.2007.02.013

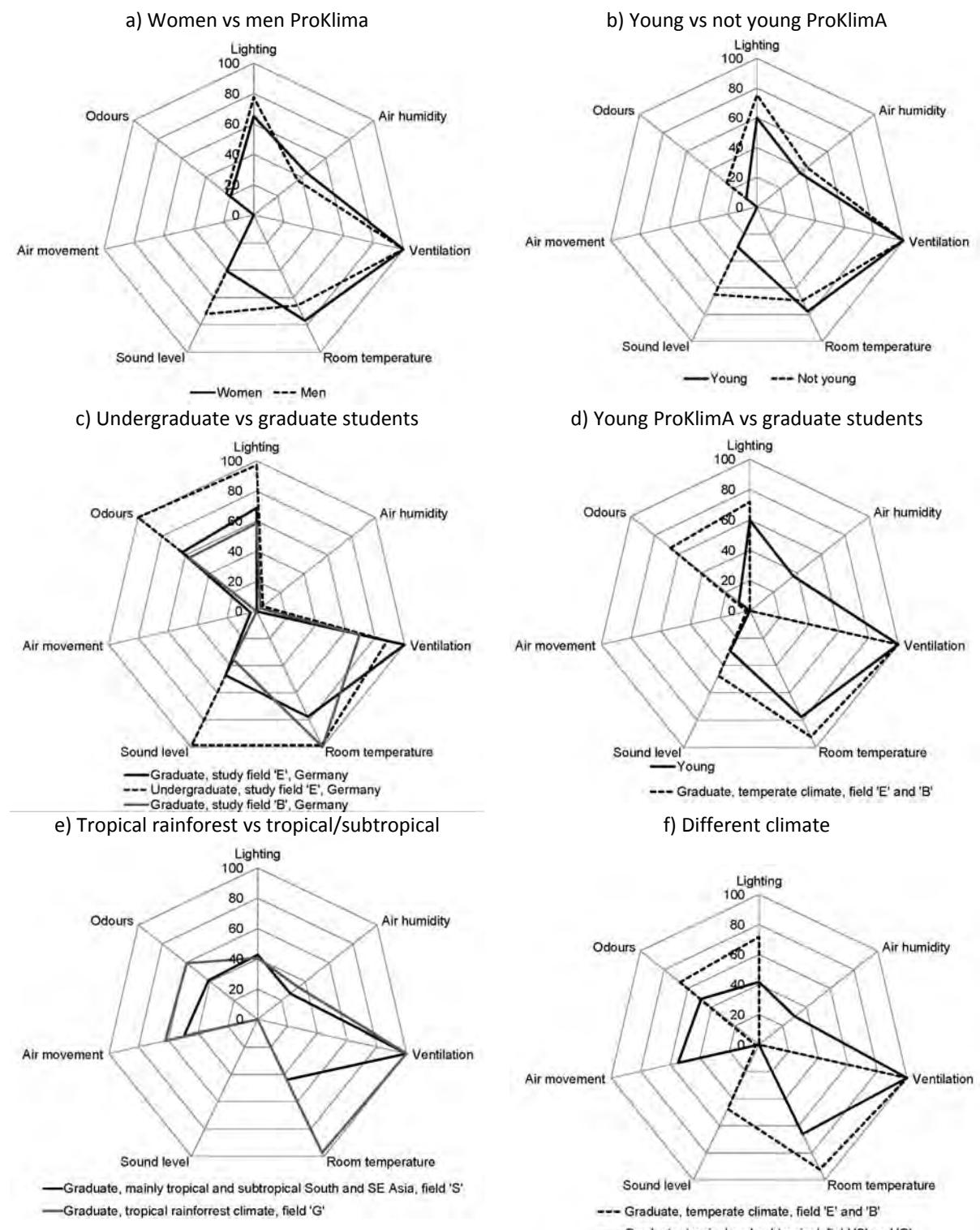


Figure 2. Radar charts of indoor environment factors ranks: a) women vs men b) young vs not young c) undergraduate vs graduate students; d) young (ProKlimA) vs graduate students field 'E' and 'B', e) graduate students field 'G' tropical rainforest climate vs 'S' mainly tropical/subtropical climates, f) graduate students from temperate vs tropical/subtropical climates



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Coping with discomfort at home and its effect on the internal climate. The case of traditional Scottish buildings before and after a retrofit

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**Abstract:** This study investigates the relationship between users and internal climate in traditional buildings. Built upon principles of social practice theory, the results presented here compare and contrast occupants' daily practices of comfort with the physical characteristics of the indoor environment. Specifically, this study explores the effect of coping with discomfort on the internal moisture loads (difference in water vapour content in g/m<sup>3</sup> between indoor and outdoor air). A cross-sectional study was designed to gather qualitative and quantitative data from households of traditionally constructed buildings before and after a thermal retrofit of the envelope. The results revealed that the 'meaning' of comfort has a crucial impact on how daily practices of comfort (such as heating or ventilation) are shaped. More importantly, the comparison between narratives and measurements showed that households where comfort was more difficult to achieve were those with higher moisture concentrations. The results of the study also showed that the adjusting mechanisms chosen by the users - that is, the way in which users coped with discomfort – and how long they lasted were heavily influenced by their perception of how easily comfort could be restored.

**Keywords:** traditional buildings, retrofit, discomfort, internal climate, practice theory

### Introduction

Internal wall insulation has a significant potential to reduce energy demand in traditional buildings. It would improve envelopes' thermal performance significantly while overcoming most of the limitations and concerns encountered when retrofitting traditional properties (cost, disruption and aesthetics) (Herrera 2016). However, long term performance of solid walls after a retrofit is still unclear due to the risk of interstitial condensation caused by the application of the insulation on the warm side of the envelope. Interstitial condensation is the result of vapour diffusion through the wall and moisture generated by occupants' activities can therefore be a crucial parameter, even comparable to wind-driven loads (Tariku et al. 2015). As illustrated by Padfield (1998), from a hygrothermal point of view, people are merely sources of water. Unfortunately, previous research has demonstrated that simplified models used to define internal climate might not be able to represent the complex interaction between users and buildings (Herrera 2016). Ultimately, hygrothermal assessment of walls' performance can only be as accurate as the definition of their boundaries and therefore further exploration of users' daily activities affect the internal climate is needed.

### Social practice theory and energy use

The importance of users' role on the reduction of energy consumption in buildings has been illustrated saying that "*buildings don't use energy, people do*" (Janda 2011). However, practice

theory principles challenged this idea based on the premise that consumption occurs in the course of engaging in particular practices. That means that consumption of energy is not a goal per se but an outcome of ordinary practices adopted by the user such as heating, eating, cooling and showering. Consumption, therefore, cannot be equalled to demand and the efforts to reduce energy consumption should be directed to the understanding of how practices that require energy are reproduced and how can be changed. This paper uses an analogous rationale for the exploration of users' impact on the indoor environment of traditional buildings. The internal climate of buildings is analysed as an outcome of users' practices of comfort (such as heating, ventilating or laundering). That is especially relevant in residential buildings where householders are most often in charge of their own comfort (Tweed et al. 2013).

Despite the agreement on the definitions of 'practice', this theory often lacks clarity and applicability in empirical research (Gram-Hanssen 2010). In this study, the approach proposed by Shove & Pantzar (2005) is adopted as it provides the most helpful framework for the empirical application of practice theory ideas (Hargreaves 2011). Shove & Pantzar structured practices around three main concepts: meaning (images or symbolic aspects of practice), materials (physical objects that are required to develop the practice) and competence (skills required to use materials according to the meaning).

## Methods

According to Yin's definition, a case study is "*an empirical enquiry that investigates a contemporary phenomenon within its real-life context when the boundaries between phenomenon and context are not clearly evident, and where multiple sources of evidence are used*" (Yin 1984, p.13). In this case, a multi-case study approach was chosen and the cases were analysed as a whole in search of common patterns. The sample was formed by 26 households of traditional buildings located in the North-East of Scotland. The dwellings, built using solid masonry granite walls and pitched roofs covered with slates, were at different levels of conservation but for the analysis buildings were categorised as "*retrofitted*" or "*non-retrofitted*" according exclusively to the insulation of the external wall. A comprehensive study of users' behaviour was carried out with the aid of interviews, questionnaires and home tours with the occupants. Interviews were focused on users' perception of comfort and their energy related patterns. Information regarding heating, ventilation and moisture production habits was collected in order to achieve a better understanding of users' interaction with the buildings. Temperature and relative humidity were monitored at 15 minutes intervals in two rooms per property (living room and bedroom). External conditions were recorded by a dedicated weather station.

## Data analysis

The purpose of a multi-case study approach was to explore dynamic processes considering them as a whole. Transcript coding of interviews and field notes was discarded as it resulted into a large compilation of disconnected concepts. Instead, this study looked at the qualitative data to reconstruct users' narratives (Paddock 2015). Exploration of narratives, as stories, has the potential to contribute to the understanding of how users structure and make sense of their comfort practices. Of the households investigated, only the narratives of four of them are presented here. This approach – similar to those adopted by Paddock (2015), Gram-Hanssen (2010) or Tweed et al. (2013) – allows for a more detailed analysis of the practices and their context. The narratives were chosen on the basis that these households represented

the most information-rich stories while presenting themes that were prevalent across the sample. The narratives selected to be presented here, although cannot be considered ideal types of any user, cover most of the topics found in the data. Besides, these narratives illustrated four very different scenarios, two cases did not have any improvement of the envelope while the other two cases had been insulated and draught-proofed. Internal climates also differed greatly, for each scenario (insulated and non-insulated) one household had low moisture loads while the other had high values.

For analysis, environmental data was sorted according to seasons. Winter (or heating season) was analysed using measurements from December to March, while summer included the measurements from June to September. Moisture loads (difference between indoor and outdoor water vapour concentration) for each room were calculated based on temperature and relative humidity recordings. Moisture load, in contrast to relative humidity, allow weighting the effect of temperature and make the comparison between households easier.

## Results

In order to facilitate the comparison between quantitative data and users' practices of comfort, a summary of households' environmental conditions and their corresponding narratives is presented in Tables 1 and 2 respectively.

Table 1. Summary of environmental conditions. Values in parenthesis represent  $\pm$  one standard deviation. T: temperature, RH: relative humidity, ML: moisture load, S: summer, W: winter, Lv: living room, Bd: bedroom.

	Case 6		Case 8		Case 12		Case 13	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
T [°C]	18.9 (1.9)	18.3 (1.6)	16.2 (1.3)	13.3 (1.4)	21.8 (1.5)	20.7 (0.9)	17.5 (2.1)	17.6 (0.5)
RH [%]	66.6 (5.8)	65.6 (6.4)	64.7 (8.3)	63.8 (5.2)	65.2 (3.5)	72.2 (2.9)	63.3 (1.9)	66.5 (3.2)
ML [g/m³]	0.8 (0.8)	0.2 (0.7)	3.2 (1.5)	1.8 (0.9)	2.5 (1.3)	3.0 (1.3)	3.9 (1.6)	4.3 (1.2)
	0.8 (0.8)	1.8 (1.3)	0.8 (1.3)	0.8 (1.3)	0.8 (1.6)	0.8 (1.1)	1.7 (1.1)	1.6 (1.1)
	1.6 (1.2)	3.2 (1.4)	1.6 (1.2)	1.6 (1.4)	1.6 (1.1)	1.6 (1.4)	1.1 (1.2)	3.1 (1.3)
	3.7 (1.5)						3.1 (1.3)	3.7 (1.5)

In Case 6, average bedroom temperature in winter was almost 3 °C lower than the living room (Table 1) as a consequence of the different use of space heating (Table 2). Relative humidity was similar in both rooms during the entire year and the different patterns of ventilation described by the user only became clear when comparing moisture loads. Average moisture load in the living room was 0.8 g/m<sup>3</sup> in summer and 3.2 g/m<sup>3</sup> in winter, while the loads in the bedroom were 0.2 g/m<sup>3</sup> (summer) and 1.8 g/m<sup>3</sup> (winter) due to higher ventilation rates. Despite the low satisfaction levels of the user in Case 8, average temperatures were considerably higher than those recorded in Case 6. It is worth noting that both dwellings formed part of the same tenement and had very similar construction characteristics. The high values of moisture load recorded in case 8 (Table 1) are in agreement with user's description of poorly ventilated rooms (Table 2).

Low average temperatures and high standard deviation values recorded in winter in Case 12 matched the description of the sporadic use of the space heating. High ventilation rates reported by the users resulted in low moisture loads (0.8 g/m<sup>3</sup> in both rooms in summer and 1.7 g/m<sup>3</sup> in the living room and 1.6 g/m<sup>3</sup> in the bedroom during the winter). Average temperatures in Cases 8 and 13 were similar but occupants' satisfaction in Case 13 was much

higher and discomfort was mainly caused by operation of the heating system and building's exposed location. The different ventilation patterns across the year resulted in different levels of moisture. During the summer, the levels of relative humidity and moisture load (1.1 g/m<sup>3</sup> in the living room and 1.6 g/m<sup>3</sup> in the bedroom) were relatively low. In winter, despite the use of a dehumidifier, moisture load results were much higher (3.1 g/m<sup>3</sup> in the living room and 3.7 g/m<sup>3</sup> in the bedroom) and comparable to those obtained in case 8.

Table 2. Summary of users' narratives of comfort at home.

	<b>Case 6</b>	<b>Case 8</b>	<b>Case 12</b>	<b>Case 13</b>
Scenario description	Victoria has lived in the same rented flat (non-retrofitted, 1 bedroom flat in the city centre) for the last 20 years. She is in her 50s and works as a waitress in a hotel. She would like to have some aspects of the flat improved but she is reasonable content in her home.	Amy lives with her new-born baby girl and a dog in a non-retrofitted 1 bedroom rented flat in the city centre. She usually works full time as an office manager but now is in maternity leave and spends most of the time at home looking after the baby.	Mark and Claire are in their 40s. They moved to a renovated two bedroom cottage a year and a half ago. They have lived in the countryside for the last twelve years. They are both outdoor people and enjoy going out for a hike or a bike ride.	Monika and Viktor live in a deeply renovated cottage with their two children and a dog. Viktor works abroad most of the time but when he is home he does not work at all. Monika is at home for most of the day, looking after the baby and working on her studies.
	Victoria likes to take a shower, cook dinner and sit in the living room in the evening. It is easy for her to be warm as 16 to 18 °C is usually enough for her. Victoria likes to have fresh air while she sleeps and the window in her bedroom is usually left open.	Being warm is the most important aspect of comfort for Amy. She has lived in the same flat for the last five years and feeling warm has always been a problem. The flat has electric radiators and storage heaters but Amy never fully learnt how they work.	Quietness is a priority regarding comfort and the main driver to choose their new home in a fairly isolated setting. They do not like being too hot or feeling that the air gets too stuffy and rather wear warm clothes at home.	Temperature is the most important factor for Monika, while Viktor is never cold and it is minor for him. He values other factors such as having a quiet environment. Their different liking in terms of comfort is also visible in the clothes they wear at home.
Coping with discomfort	Living room windows are usually closed. She finds the noise from the traffic too loud and prefers to keep it shut. She only opens the window when she is cooking something very steamy in the open plan kitchen. The extractor fan is also very noisy and is not used often either.	Amy decided to buy a portable bottled gas heater after a cold winter and has been using it since then. All doors in the flat are kept closed and fitted with draught excluders. The bedroom window is also permanently shut and it has been partly covered with an insulating board.	They usually do not use the heating for more than three hours a day. If they feel cold, Mark would sooner light the stove than using the oil boiler. They never leave the fire on overnight as he does not mind lighting it again the next day if they need it.	A wood burning stove feeds both the heating and hot water, so they have to keep it on during the day. The house is in a very exposed location and airing the rooms when it is raining is not possible. Instead, they bought a dehumidifier. It is also very helpful for drying laundry.

## Coping with discomfort: the effect of how easily comfort can be restored

Within the small sample of four narratives presented here, very different meanings of comfort were found. Beyond the differences in meanings, what the comparison between narratives and measurements showed was that those households where comfort was more difficult to achieve (whatever meaning it had) were those with higher moisture concentrations.

The principle of adaptive comfort states that "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" (Nicol et al. 2012). Therefore, high moisture loads appeared to be a consequence of practices developed by the users to cope with discomfort. Literature on discomfort in buildings usually classify those mechanisms of adjustment as: (i) environmental or technological (interaction with the building control systems such as heaters or fans), (ii) personal or behavioural (changing activity, clothing or posture) and (iii) psychological (managing emotions or thoughts about the situation) (Heerwagen & Diamond 1992; Azizi et al. 2015).

According to Shove & Pantzar (2005), the links between the elements of a practice are reproduced and maintained by the practitioners, represented as 'carriers'. Moreover, practices emerge, develop and disappear as a consequence of the formation or dissolution of these links. New practices can therefore be generated by breaking the links between elements of existing practices and re-making them in a different manner (Hargreaves 2011). Coping with discomfort, therefore, cannot be considered as a practice on itself but as an adaptation of the practices of comfort at home (including heating, cooking or ventilating). Moreover, the three mechanisms of adjustment described above can be easily likened to the elements of practices proposed by Shove and Pantzar: environmental as material, behavioural as competence and psychological as meaning.

The results of this study showed that the adjusting mechanisms chosen by the users (that is, the way in which users coped with discomfort) were heavily influenced not only by their comfort expectations but also by their perception of how easily comfort could be restored. If comfort was quickly achieved after the cause of discomfort ceased, then users mainly engaged in temporary adjustments of material or competence (wearing a pullover on a cold night or closing the window if the road is too busy and loud). These changes were meant to provide "*rapid and noticeable changes in the environment*" (Heerwagen & Diamond 1992). When the cause of discomfort ceased the practices returned to their normal configuration and comfort was recovered easily. Thus, since the reaction to discomfort did not endure, the adjusting mechanisms did not break any link between the elements of the existing practices and did not produce any lasting change in the internal climate.

On the other hand, the adjusting mechanisms adopted by users that felt that comfort was difficult to restore were almost permanent and involved changes in all the elements of practice (and the links between them) that resulted in new practices. The coping approaches were essentially of two types: the adaptation of the meaning or the modification of the material structure. In the first case, the meaning of comfort at home was altered to match the actual conditions of temperature, humidity, noise, etc. that could be achieved with the available materials and competences. Heerwagen & Diamond (1992) explains this mechanism in plain terms saying that the users try to ignore the discomfort or "*just put up with it*".

Temperature was inarguably the first aspect mentioned by the majority of occupants when asked about comfort. However, the definition of thermal comfort differed from one case to another. Thus, some users felt comfortable with temperatures in the range of 16-18 °C while other occupants were dissatisfied with even higher levels of internal temperature. This discrepancy in the expectations of thermal comfort was constant throughout the entire

sample. Users that felt comfortable with lower temperatures tended to have a common ‘image’ of comfort adapted to traditional buildings. Among those users, there was a shared perception that “*old is cold*” (Ingram et al. 2011) and the expectations of thermal comfort were adjusted since no higher internal temperatures could be achieved. In those cases, the practices of comfort were permanently reconfigured but only involved the modification of one element (the meaning of thermal comfort) and resulted in environments with low moisture loads (Case 6).

Warmth or internal temperature was not the only aspect of comfort that occupants had in mind when thinking about their homes. In fact, warmth was not the most important factor in many cases. Fresh air, quietness, privacy and cleanliness were also important factors for several occupants. In those cases, the internal temperature stayed in the background when talking about their comfort at home. These occupants were willing to sacrifice thermal comfort, to some extent, by accepting lower levels of internal temperature if other aspects of comfort were fulfilled (Case 12).

A second coping approach consisted in the modification of the material structure and its operation in order to create an environment that matched users’ predefined images of comfort. The narrative of Case 8 is a clear example of how the material structure was modified (new portable bottled gas heater; windows, trickle vents and curtains shut; bedroom window covered with an insulation board) as a response to an environment that did not match the expectations of comfort at home (steady high temperatures). In those cases, the mechanisms of coping with discomfort consisted in the reconfiguration of both heating and ventilation practices and involved permanent changes to the material structure that were reflected in the internal environment in the form of high values of moisture load.

## Discussion

Although quantitative studies in the area of residential buildings are very scarce (Tweed et al. 2013), reaction to discomfort in working places have already been explored in previous studies. Azizi et al. (2015) found a relationship between the material structure of office buildings and how the users’ meaning of comfort is adapted to cope with discomfort. Azizi stated that occupants of ‘green’ buildings were more likely to accept discomfort and that they were “*engaged in less environmental adjustments, and adopted more personal and psychological coping mechanisms than those occupants in the conventional building*”. In this study, a relationship between material and meaning was only found among the occupants of traditional buildings who shared the perception that ‘old is cold’. As a consequence, they accommodated their expectations of comfort to this pre-established image and adapted their practices accordingly.

Nevertheless, no correlation between the level of insulation of the building and adaptive comfort practices was found. The results of this study challenge the idea that users of better performing dwellings “*have lower thermostat settings but air their dwellings more often*” creating healthier environments (Raaij & Verhallen 1983). According to the narratives’ analysis, meaning of comfort has proven to be more determining than the physical properties of the building. This investigation, therefore, aligns more closely with the conclusions from an earlier study on energy saving houses (Hamrin, 1979, in Raaij & Verhallen 1983) that linked the final success of the energy efficient measures (material) to the energy consciousness of the users (i.e. the meaning). Hamrin found that passive equipment, that involves active engagement of users, is better suited to residents with high levels of energy consciousness.

The conclusions of Hamrin's study – i.e. the type of system (material) should match occupants' meaning of comfort – can be directly extrapolated to this research.

The results of this study also discovered a relationship between the perception of how easily comfort could be restored and the practices finally adopted. Every user occasionally felt uncomfortable and therefore adapted their practices to restore the comfort. However, only those users that were not able to restore their comfort quickly engaged in practices that had a negative lasting effect on the internal climate. A high level of adaptation made by the users to feel comfortable was also reported by Heerwagen & Diamond (1992). In their work, they introduced the term "*coping success*" to describe the ability to effectively resolve discomfort. They also suggested that designers should include more opportunities of personal control to avoid environmental (material) changes and to increase coping success. In line with Heerwagen & Diamond's recommendations, the results of this study highlight the need to facilitate 'safe' or 'compatible' options of adaptation that can provide users with comfort at home while preventing any scenarios of high moisture concentration.

Gram-Hanssen's (2010) work found that standby consumption was the outcome of a series of dispersed practices rather than an integrated practice. She argued that campaigns to make people aware of their standby consumption are trying to convert their dispersed habits into an integrated practice. Analogously, the results of this study showed that internal climate is an outcome of a series of dispersed practices and therefore making people aware of their effect on the indoor environment could connect dispersed practices like laundering and ventilating forming one new integrated practice

## Conclusion

There is a large body of literature using quantitative approaches to explore the use of domestic space heating (Guerra-Santin & Itard 2010), ventilation (Fabi et al. 2012) or laundry appliances (Porteous et al. 2014). However, the results of such studies have proven to be insufficient to explain the mechanisms of user behaviour and often reached opposite conclusions (Wei et al. 2014). This study opted in favour of a more qualitative approach to explore users' effect on the internal environment of traditional buildings. Thus, this research carried an in-depth exploration of the narratives of comfort at home in order to identify the reasons behind users' behaviours.

The results presented here aligned with those obtained by Tweed et al. (2013) who stated that being thermally comfortable has different meanings to different users. The results of this investigation, however, did not only point to the differences in thermal preferences but also to the different meanings of practicing comfort at home. As stated by Madsen (2014), comfort is not limited to temperature as it also includes aspects like "*light, functionality and homeliness*".

The results of this study corroborated the relevance of discomfort in shaping the internal environment of buildings. Practices developed to tackle discomfort were shaped to create the conditions that users considered acceptable, regardless of those predicted by conventional comfort theories (Tweed et al. 2013), and ignored their effect on the indoor environment. Consequently, adapted practices of comfort at home often resulted in poor environments with high concentrations of humidity and low air change rates. Efforts to explore the role of users on the internal climate of traditional dwellings should be directed to understand how the practices of comfort that affect the environment are reproduced and how can be changed.

## References

- Azizi, N.S.M., et al., 2015. An Analysis of Occupants Response to Thermal Discomfort in Green and Conventional Buildings in New Zealand. *Energy and Buildings*, 104, pp.191–198.
- Fabi, V., et al., 2012. Occupant window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58, pp.188–198.
- Gram-Hanssen, K., 2010. Standby consumption in households analyzed with a practice theory approach. *Journal of Industrial Ecology*, 14(1), pp.150–165.
- Guerra-Santin, O. & Itard, L., 2010. Occupants' behaviour: determinants and effects on residential heating consumption. *Building Research & Information*, 38(3), pp.318–338.
- Hargreaves, T., 2011. Practice-ing behaviour change: Applying social practice theory to pro-environmental behaviour change. *Journal of Consumer Culture*, 11(1), pp.79–99.
- Heerwagen, J. & Diamond, R.C., 1992. Adaptations and Coping: Occupant Response to Discomfort in Energy Efficient Buildings. In *1992 Summer Study on Energy Efficiency in Buildings*. Washington, pp. 83–90.
- Herrera, D., 2016. Energy efficiency improvements in traditional buildings. Robert Gordon University, PhD thesis
- Ingram, V., Banfill, P.F.G. & Kennedy, C., 2011. Towards an objective assessment of energy efficiency in heritage buildings. In *World Renewable Energy Congress*. Linköping, Sweden.
- Janda, K.B., 2011. Buildings don't use energy: people do. *Architectural Science Review*, 54(1), pp.15–22.
- Madsen, L.V., 2014. Can Comfort Be Practised? In *BEHAVE2014*. Oxford.
- Nicol, F., Humphreys, M. & Roaf, S., 2012. *Adaptive Thermal Comfort*, Oxon: Routledge.
- Paddock, J., 2015. Household consumption and environmental change: Rethinking the policy problem through narratives of food practice. *Journal of Consumer Culture*. 17(1), pp. 122-139
- Padfield, T., 1998. The role of absorbent building materials in moderating changes of relative humidity. PhD Thesis. The Technical University of Denmark.
- Porteous, C.D. a. et al., 2014. Domestic laundering: Environmental audit in Glasgow with emphasis on passive indoor drying and air quality. *Indoor and Built Environment*, 23(3).
- Raaij, W.F. Van & Verhallen, T.M.M., 1983. Patterns of residential energy behaviour. *Journal of Economic Psychology*, 4, pp.85–106.
- Shove, E. & Pantzar, M., 2005. Consumers, Producers and Practices: Understanding the invention and reinvention of Nordic walking. *Journal of Consumer Culture*, 5(1), pp.43–64.
- Tariku, F., et al., Experimental investigation of the wetting and drying potentials of wood frame walls subjected to vapor diffusion and wind-driven rain loads. *Building and Environment*, 92(2015), pp.368-379.
- Tweed, C. et al., 2013. Thermal comfort practices in the home and their impact on energy consumption. *Architectural Engineering and Design Management*, 10(1-2), pp.1–24.
- Wei, S., Jones, R. & de Wilde, P., 2014. Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings*, 70, pp.36–44.
- Yin, R.K., 1984. *Case Study Research. Design and Methods*. 3<sup>rd</sup> Ed., London: SAGE Publications.



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*Design to Thrive*

## Colour as a psychological agent to manipulate perceived indoor thermal environment for low energy design; cases implemented in Sri Lanka

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**Abstract:** Achieving indoor thermal comfort via innovative, sustainable, energy efficient approaches is a contemporary research mission world-wide. Colour, being a characteristic property of any indoor environment, has rarely been considered for its thermal impacts in this regard, especially in distinguishing a dichotomy of colour perception in thermal terms. The current paper examines the potential of Colour associated Thermal Perception (CTP) to psychologically manipulate perceived indoor thermal environment of inhabitants against the 'real' thermal conditions of indoor environments. If done correctly, this may enable the inhabitants to reach comfort levels consuming comparatively less energy leading to a potential hybrid method of energy conservation. Based on a series of empirical studies in Sri Lanka, the paper reveals CTP to be a psychological response and confirms the common perception of red colour as warm against blue as cool irrespective of the fact that the subjects are normal sighted, colour blind or even blind. Further work revealed that incorporating red colour in interiors of cool tropical uplands (Thalawakele, Sri Lanka, Altitude = 3,930 ft, 6.9388° N, 80.6632° E ) is supportive of psychologically inducing a comparatively warmer thermal perception against the real (cold) thermal condition, resulting in reduced heating costs. The reverse was true in hot, humid coastal areas (Panadura, Sri Lanka, Altitude= 3ft, 6.7202° N, 79.9305° E) where factory workers demanded increased ceiling fan speeds to achieve thermal comfort in red coloured interiors whereas lower fan speeds were sufficient for thermal comfort when exposed to blue colour. Accordingly, integrating the shades of cool colours (blue, green, purple) in the interiors of a hot humid climate and warm colours (red, yellow, orange) in cold climate is recommended as a highly supportive low cost solution in reducing the heating and cooling costs respectively, leading to energy conservation.

**Keywords:** Thermal perception, Warm colours, cool colours, thermal comfort, Energy conservation.

### Introduction

The share of energy demand in buildings (over 40% of total global consumption, Perez-Lombard et al., 2008) is increasing globally on account of economic development. The contribution of space conditioning to this increasing demand (currently 62% of the total building energy need, IPCC, 2013) is being made worse by the changing climate, especially in warm climates (Sillmann et al., 2013, Emmanuel, 2017) . Designing buildings that require less or zero energy to achieve 'thermal comfort' of occupants is therefore more vital today than ever before. Transcending beyond active, energy-intensive interventions, many innovative, passive or low energy design strategies have evolved to address this need. Building location and orientation based on sun path and wind movement, energy efficient built forms and layouts, well designed shading devices, thermal insulation, contextually appropriate building envelopes, incorporating appropriate behavioural patterns of

occupants and introducing energy-efficient lighting and electronic appliances are few such established passive cooling strategies in warm climates (Santamouris and Asimakopoulos, 1996). Further, incorporating passive cooling strategies which rely on natural heat sinks to modulate heat gain with thermal mass and heat dissipation via natural cooling techniques; natural ventilation, radiate cooling, evaporative cooling, earth coupling etc, have also been considered (Santamouris and Asimakopoulos 1996, Lechner 2009).

Meanwhile, the definition of "Thermal comfort" is being re-questioned beyond its long held conventional understanding of a physiological response to thermal stimuli to be a psychophysiological response by several scholars. Revealing the extremely subjective nature of comfort, de Dear (2011) stated that one man's breeze is another man's draft. According to Ogoli (2007), thermal comfort is a process moulded with past experiences and memories and humans perceive and respond to the same thermal experience in a manner unique to each one. In a study by Hoppe (2002), simply announcing that the temperature was higher than it really was, made the occupants to start feeling warmer. Rohles (1980 as cited in Hoppe, 2002) found that, just adding additional material that gave the look of thermal insulation - wood panels, carpets, furniture - made the occupants feel warmer even though none of the thermal parameters had actually changed. These findings signify the role played by psychological aspects in terms of perception of thermal comfort. Accordingly, the current paper aims at evaluating the potential of colour to psychologically manipulate the perceived thermal environment with a view of exploring it as a strategy to achieve comfort as a future projection. Heat absorbing / heat reflecting properties of colour: Light Reflective Value (LRV) is already being used as an effective strategy to conserve energy (Morton, 2012) and is not the focus of this discussion. The current paper focuses on a less investigated, yet a vital association; colour associated Thermal Perception (CTP) as a potential strategy to manipulate thermal comfort.

## **Background**

Colours have been explained in thermal terms (Mahnkey, 1996) and are said to alter human thermal perception. The philosophical theory of colour, pioneered by artists and established as a tradition of colour mixing with long-term practice, explicitly differentiates between warm and cool colours. Even though not satisfactorily explained via scientific inquiry, colour theory identifies red, yellow and orange as warm and blue, green, and purple as cool. Warm colours are said to have a stimulating impact on humans where-as cool colours are described to have a pacifying effect (Fanger et al, 1977, Mahnkey, 1996, Stone 2001 and Ballast, 2002).

Colours have been widely utilised in the interiors for beautification, to manipulate perceived dimensions of space and to trigger thoughts, feelings, emotions and behaviour of occupants parallel with the corresponding ambience to be generated. A considerable amount of research in the fields of experimental psychology, applied psychology and psychological ergonomics has been done on the possible influence of colours or coloured surfaces on thermal sensation and thermal comfort (Albers et al, 2013). However, the thermal impact of colour has not been utilized in interiors to draw its fullest benefits. Supportive evidence on the thermal effects of colours in the 20<sup>th</sup> century is found to be substandard (Hettiarachchi, 2014). No effects of colour on temperature perception are found in many such studies (Berry 1961 and Green & Bell 1980) or observed effects were very small and considered at that time to be of no practical significance (Fanger et al, 1977). It has long been assumed that the impact of visual and thermal stimulation is interactive,

yet this long-held belief has accumulated surprisingly little experimental support (Candas and Dufour, 2005). Furthermore, there is a significant lack of experimental evidence on CTP with reference to eastern/Asian region. In order to fill this gap, the current paper reports three investigations in attempting to understand the nature of CTP and test the possibility of integrating CTP as a novel alternative strategy for energy conservation in buildings by altering the perceived indoor thermal comfort levels against the real thermal level within interiors in a hot humid tropical and tropical upland regions in Sri Lanka.

**Case 1: Colour associated thermal perception: manifestation and contributing factors With reference to red and blue**

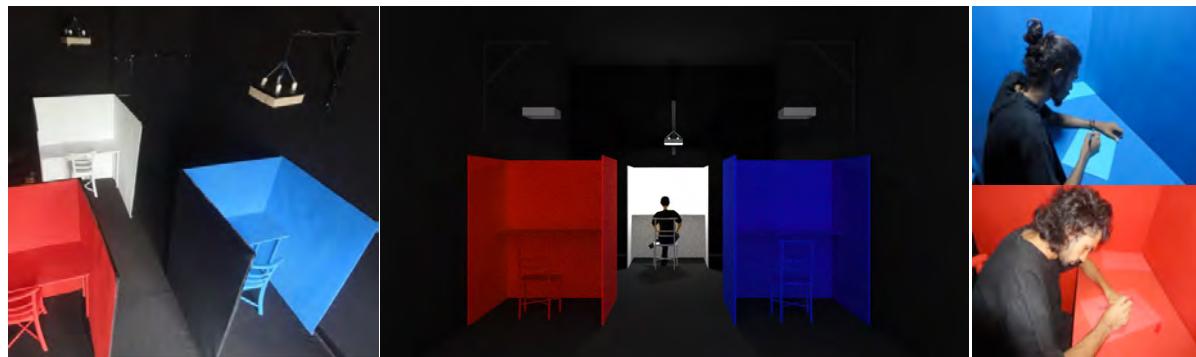


Figure 1. Controlled lab environment with colour workstations

Case 1 claims its originality in substantiating a scientific explanation on manifestation and contributing factors of CTP with reference to a warm colour (red) and a cool colour (blue) as applicable to Asian context [Hettiarachchi,2014]. Hypothesised potentials of CTP to manifest as (a) a psychological response, (b) a biological response altering core body temperature or (c) an actual thermal sensation caused due to heat radiation emitted via coloured surfaces were tested. A crossover experiment was executed in colour workstations (WS) with a sample of healthy, normal sighted male undergraduates ( $n=111$ , selected via stratified simple random sampling, age 19 – 30, 95% confidence level, 7.5% margin of error) under controlled laboratory conditions (26°C room temperature and 50% relative humidity, 350 lux lighting level) and interior finishes (matt) and colour (black).

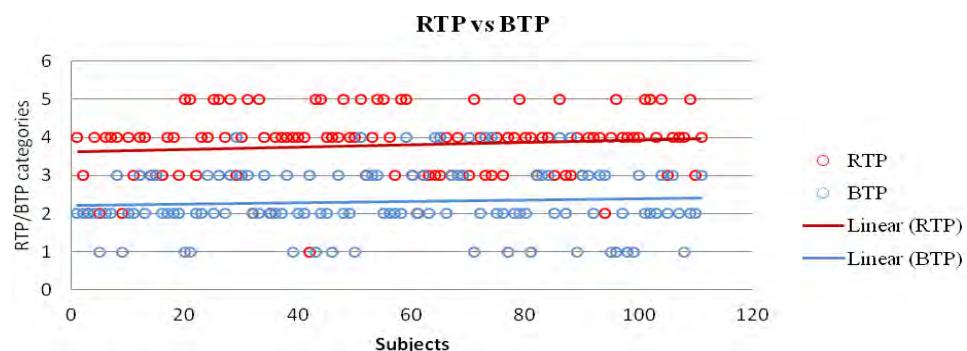


Figure 2: Scatter Plot-Thermal Perception in Red WS (RTP) vs. Thermal Perception in Blue WS (BTP)

CTP was rated on a 5 - point Likert scale by the participants while the induced feelings, emotions and preference to each colour treatment were recorded via a questionnaire survey. Temporal artery temperature of subjects and the surface temperature of work stations were recorded through infrared thermal monitoring. The data related to 18

potential parameters were analysed adopting a Complex Sampling Ordinal Logistic Regression model.

Validating the colour theory, subjects demonstrated a propensity to perceive red as warm/hot (64.2%) and blue as cool/cold (59.3%). As depicted by the scatterplot of RTP Vs BTP, RTP was found to be significantly warmer than BTP (figure 2). Logistic regression showed CTP manifests itself neither as a fluctuation in core body temperature nor as an actual thermal sensation. It was thus identified to be a psychological response characterised by common as well as colour specific factors. CTP of both red (RTP) and blue (BTP) are statistically explained by the psychological state induced by each colour, pre-conceived learnt ideas influenced by education, and subjects' preference. Favourite colour and religion of the subjects were found to influence RTP while subject's age and surface temperature of the applied colour were revealed to influence BTP. Thus, integration of CTP in built environment to psychologically manipulate the perceived thermal environment against the actual thermal condition is a possibility.

Case 1 also tested five totally colour blind subjects (identified by the Ishihara Test for colour-blindness, Ishihara, 1917) via the same research design. Majority (80%) of subjects reported to perceive a warm RTP while 20% rated RTP to be neutral. Contrasting the normal subjects, these subjects showed a tendency to witness a neutral BTP (60%) while only 40% perceived blue to be cool. No one perceived blue WS to be warm (0%) and red WS to be cool (0%) (Hettiarachchi, 2014). Colour-blind subjects, though theoretically unable to see colour via visual perception process, were found to experience a thermal perception in dual nature associated with red and blue colour similar to the perception of normal sighted subjects. This opens up novel research directions on possibilities of CTP to take place via other paradigms of perception apart from vision; supposedly via the skin, human energy field via vibration or synesthesia.

Following the same line of thinking 20 nos of blind subjects were tested by introducing red, blue, yellow and white fabrics to their learning environment [Grade 6-A (n=7), Grade 7-A (n=6 ) and Grade 7-B (n=7 ), age : 11-12] in a School for the blind in Sri Lanka (Priyadarshani, 2015). Their responses to colour were obtained via a questionnaire survey using braille system with the assistance of class teachers. Red colour was found to be significantly warm and uncomfortable; 89.4% (neutral; 10.5%) while blue was reported to be cool and comfortable; 80% (neutral: 15%, warm: 5%). Yellow was felt as either warm (55.5%) or neutral (44.4%) and white was found to be neutral (68.4%) by many and as cool (26.3%) by others.



Figure 3: Colour perception test at a School for the blind in Sri Lanka (11 -12 yrs old subjects)

Above findings confirm the common perception of red colour as warm and blue as cool irrespective of the fact that the subjects are normal sighted, colour bind or even blind. This further strengthens the possibility to use CTP as a tool to psychologically manipulate perceived indoor thermal environment at lower energy costs.

### **Case 2: Colour as a tool to manipulate indoor thermal perception in tropical upland climate; a field experiment implemented in Sri Lanka**

As an alternative hybrid remedy for energy conservation in tropical upland climate, integrating warm colours in the interiors was attempted in case 2 to help the inhabitants to perceive the indoor thermal environment as warmer than the actual condition, thus compensating the heating costs to some extent. A preliminary field experiment was executed to investigate the impact of a warm colour (red - Cranberry Zing) and a cool colour (Duck egg blue) on indoor thermal perception of subjects in tropical upland climate (Thalawakele, Sri Lanka; Altitude = 3,930 ft, mean annual temperature: 18°C ). A sample of seven identical houses from a housing scheme (upper Kothmale hydropower project) having the same layout, orientation and identical method of construction, materials and finishes were selected to execute this field investigation. Two colours were introduced to an identical wall of two adjoining identical rooms while leaving three walls of each room in white colour. The subjective perceptions of 31 participants (17 males and 14 females) were transformed into objective data with the use of a 5 point likert scale which is a reduced version of the standard thermal comfort scale (ISO 7730). The indoor temperature of red vs blue room in all the seven houses against outdoor temperature were monitored via a digital thermometer from 6.00 a.m to 8.00 p.m (Welitharage & Hettiarachchi, 2014).

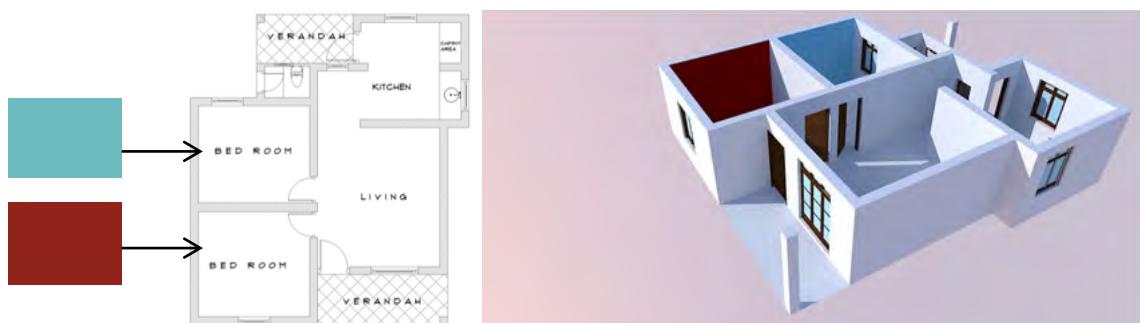


Figure 4. Plan and 3D view of the identical bedrooms after colour application.

The subjects admitted perceiving a variation in the room temperature induced due to the new colour scheme (70.9% strongly agree, 29% agree). Validating the hypothesis, participants consistently perceived red room to be warmer and thermally comfortable 100% (90% - warm and 10% - slightly warm) while blue room was perceived to be even cooler 93.5% (64.5% - cool/ 29% - slightly cool) and 6.5% remained neutral. Red colour was found to induce a warmer thermal perception against the actual cold thermal condition even if no significant difference between the indoor temperature of rooms having a red wall and a blue wall was reported (average 22.3°C in both rooms) (Welitharage & Hettiarachchi, 2014). Parallel to the findings of case 2, Morton (2012) reports that people estimate the temperature of a room with cool colours, such as blues and greens, to be 6 -10°F cooler than the actual temperature.

Testing the same principle with interiors in the Sri Lankan context, where a heating system or a cooling system is involved, was attempted as the next level of the investigation to identify the potentials of reaching indoor thermal comfort with less energy usage.

### **Case 3: Thermal Impact of colour as an Energy Saving Strategy in Hot Humid Tropical Climate: a Field Experiment implemented in Panadura, Sri Lanka**

The potential of incorporating CTP in hot humid tropical climate as an energy saving strategy was tested by this investigation with reference to an industrial building characterized by high energy consumption. A garment factory located in Panadura (Altitude= 3ft, 6.7202° N, 79.9305° E, mean annual temperature: 26.9°C) which extensively utilizes mechanical ventilation (ceiling fans) demanding a high level of energy consumption was investigated. It was hypothesized that cool colours may psychologically induce a cool thermal perception against the real warm conditions leading to reducing cooling costs (Wijeratne & Hettiarachchi, 2015). Existing white colour was replaced initially by red (warm colour) followed by blue (cool colour) using colour fabric, anticipating opposite reactions. Fan speed was manipulated until the subjects reached the thermally comfortable level with reference to the colours introduced. Research was conducted within six working days and the responses were recorded via a questionnaire survey. Indoor temperature of the factory and outdoor temperature were recorded throughout the day via digital thermal monitoring.



Figure 5. Colour fabric introduced to the factory interior

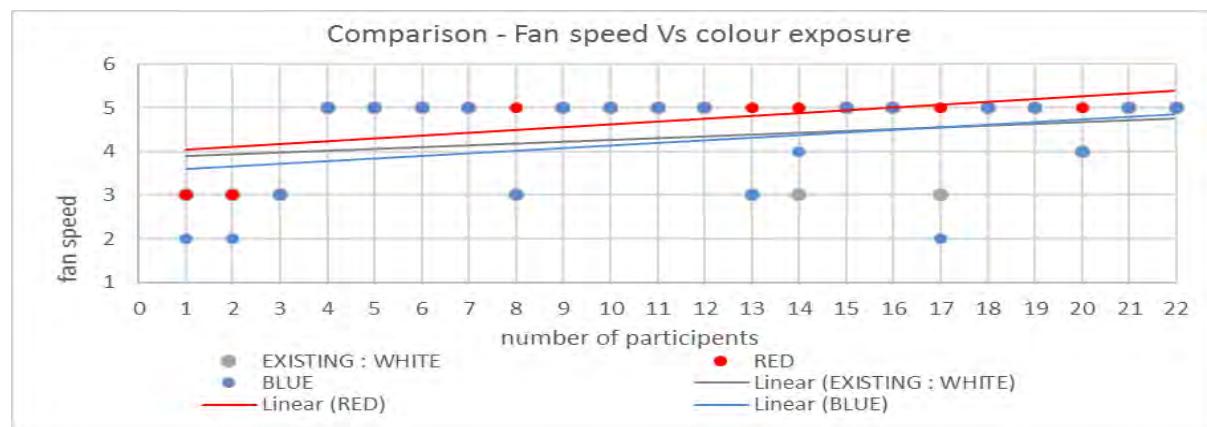


Figure 6. Comparison between selection of fan speed vs colour of the factory interior

The research investigated on the impacts of colour on workers (machine operators) in terms of their thermal perception by changing the colour of the interior walls of the factory space. The study established a correlation between the interior colour and the preferred fan speed in achieving thermal comfort. Majority of workers (86.36 %) were found to achieve their thermal comfort with the maximum fan speed (speed level 05) when exposed to colour red demanding a high energy consumption, while, only 13.63 % preferred a moderate speed (speed level 03) with an average indoor temperature of 31.5 °C and outdoor temperature of 32.2 °C. 63.63 % were satisfied with level 05 while 9%, 13.63% and

13.63% achieved thermal comfort in speed levels 04, 03 and 02 respectively when exposed to blue fabric even with an average indoor and outdoor temperature of 32°C and 33 °C respectively. It is evident that colour blue has been supportive in achieving perceived thermal comfort at a comparatively lesser level of energy consumption (figure 6). Psychologically induced cooling impact of blue has been highly supportive in the perception of a comparatively cool indoor thermal level to reach the comfort threshold amidst the actual warm conditions even with 0.5 °C increase of average indoor temperature compared to red exposure. Incorporating color blue (cool colors in general) was found as a highly favorable alternative strategy of energy conservation in hot humid tropical climate in Sri Lankan (Wijeratne & Hettiarachchi, 2015). These findings confirm a Norwegian study where subjects tend to set the thermostat 4 degrees higher in a blue room than in a red room (Tom and Micelles, 1976). Further, Clerk (1975) reported that the employees who complained of the cold in an air-conditioned factory cafeteria with light- blue walls when the thermostat was set at 75 ° F considered the room too warm and reduced the thermostat to 72 ° F once the walls were repainted orange. Affirming the same, a study executed by Itten (1961 cited in Mahnke, 1996) demonstrated a difference of 5 – 7°F in the subjective feeling of heat or cold between workrooms painted blue-green vs. red- orange. Occupants of the blue- green room felt 59° F as cold, whereas the temperature had to fall to 52° F in the red- orange room before the subjects felt cold. Taking a different approach, Winzen et al (2013) attempted to test the impact of warm vs. cool LED lighting scenarios to conserve energy in aircraft aviation industry. Subjects reported slightly warmer thermal sensations in yellow light and slightly colder sensations in blue light resulting in a slightly higher satisfaction with the (whole) climate situation in yellow light within the aircraft interior, signifying potential of lighting in energy conservation.

The present study therefore leads to the recommendation that colours can be incorporated as an alternative, hybrid strategy in achieving indoor thermal comfort with less energy use via its ability to psychologically influence the perceived thermal environment. Integrating shades of warm colours in indoor spaces of cool climatic regions can psychologically induce a warmer thermal perception against the actual thermal condition in occupants, compensating heating costs. On the other hand application of shades of cool colours in interiors of a warm climatic region can psychologically manipulate occupants to perceive the environment as cooler than the actual condition, saving energy costs on cooling. Even if the psychologically induced impact of colour on thermal perception and thermal comfort is minimal, when applied in a large-scale this strategy may potentially lead to a quantifiable influence on energy savings at a national level. Developing the use of applied colour as an effective and affordable hybrid method of energy conservation backed with long term investigations is proposed and formulating energy conserving design strategies with the use of colour is highly suggested.

## References

- Albers, F.,Winzen, J and Marggraf-Micheel. (2013). In search of evidence for the hue-heat hypothesis and its possible energy and cost-effective application in the aircraft cabin, Retrieved from <http://www.dglr.de/publikationen/2013/301236.pdf>
- Ballast, D. K. (2002). Interior design reference manual. Professional Pub. Inc.:Belmont, CA.
- Berry, P.C. (1961). Effect of colored illumination upon perceived temperature. *Journal of Applied Psychology*, 45, 248-250.
- Candas V, Dufour A. (2005). Thermal comfort: multisensory interactions? *Journal of Physiological Anthropology and Applied Human Science*. 24(1):33-6.PMID:15684540.

- Clark, L. (1975). *The Ancient Art of Color Therapy*. Old Greenwich, CT: Deving-Adair.
- De Dear, R.J. (2011). Revisiting an old hypothesis of human thermal perception: Alliesthesia, Building Research & Information, Volume 39, Issue 2, 2011.
- Emmanuel R, 2017. Performance standard for tropical outdoors: A critique of current impasse and a proposal for way forward, *Urban Climate*, DOI: 10.1016/j.uclim.2017.01.002
- Fanger, P, Breum, N. & Jerking, E. (1977). Can colour and noise influence man's thermal comfort? *Ergonomics*, 20, 11-18.
- Green, T.C. & Bell, P.A. (1980). Additional considerations concerning the effects of 'warm' and 'cool' wall colours on energy conservation. *Ergonomics*, 23, 949-954.
- Hettiarachchi, A.A. (2014). Colour Associated Thermal Perception, Manifestation and contributing factors with reference to red and blue. PhD. University of Moratuwa.
- Hoppe,P.(2002). Different aspects of assessing indoor and outdoor thermal comfort, *Energy and Buildings*, 34, p.p 661-665.
- Ishihara,S.(1917), Tests for color-blindness ,Handaya, Tokyo, Hongo Harukicho.
- Lechner, N (2009). Heating,Cooling, Lighting: sustainable design methods for architects (3rd ed.). 605 Third Avenue, New York, NY 10158-0012, USA: John Wiley & Sons, Inc. ISBN 978-0-470-04809-2.
- Mahnke, F. H. (1996). *Color environment & human response*. Canada: John wiley&sons.
- Morton, J.(2012).Color & Energy Matters, Retrieved from <http://www.colormatters.com/color-and-science/color-and-energy-matters>
- Ogoli,D.M. (2007). Thermal Comfort in a Naturally-Ventilated Educational Building, ARCC Journal; Volume 4 Issue 2, pp.19-26.
- Pérez-Lombard, L., Ortiz, J., Pout, C. 2008. A review on buildings energy consumption information, *Energy and Buildings*, 40, (3), pp. 394–398
- Priyadarshani, S.(2015).Impact of Colour on Visually Impaired Children; a field experiment implemented in Blind School, Rathmalana, Sri Lanka. B.Arch. Univresity of Moratuwa.
- Santamouris, M.; Asimakopoulos, D. (1996). *Passive cooling of buildings* (1st ed.). 35-37 William Road, London NW1 3ER, UK: James & James (Science Publishers) Ltd. ISBN 1-873936-47-8.
- Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., Brionaugh, D., 2013. Climate extreme indices in the CMIP5 multi-model ensemble. Part 2: Future climate projections. *J. Geophysical Research – Atmosphere*, 118(6): 2473-2493, DOI: 10.1002/jgrd.50188.
- Stone, N. (2001). Designing effective study environments. *Journal of Environmental Psychology*, 21(2), 179-190.
- Tom,P and Mikellides, B.(1976). *Colour for Architecture*, New York: Van Nostrand Reinhold.
- Welitharage, M. & Hettiarachchi, A.A., (2014). Colour as a tool to manipulate indoor thermal perception in cold climatic regions. In: National Energy Symposium – 2014, Colombo, Sri Lanka 21st November 2014. Colombo: Sri Lanka Sustainable Energy Authority of Environment & Renewable Energy.
- Winzen, J, Albers, F. & Marggraf-Micheel, C. (2013). The Influence of coloured light in the air-craft cabin on passenger thermal comfort. *Lighting Research and Technology*, 0, 1-11 (online first publication; DOI: 10.1177/1477153513484028).
- Wijeratne. W.H.P & Hettiarachchi, A.A. (2015). Thermal Impact of Colour as an Energy Saving Strategy: A Field Experiment Implemented in Sri Lanka. In: 3rd International Conference on cities, People and Places, ICCPP-2015 on Towards New Urbanity – Places for Urban Coherence, Colombo, Sri Lanka, 27th October 2015. Moratuwa: Department of Architecture, University of Moratuwa.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Evaluation of the PET thermal comfort index calibration methods used in Brazil

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**Abstract:** A calibrated thermal comfort index, which can represent human thermal sensation in a numerical way, is a valuable tool for evaluating thermal conditions in urban areas. Brazil, a continental size country, presents eight different climate zones according to its bioclimatic zoning standard. Due to its area extension and climate diversity, thermal comfort indexes must be calibrated to each city to better represent the different thermal sensations of each local population. In Brazil, the Physiological Equivalent Temperature (PET) index, widely applied in outdoor evaluations, has already been calibrated for some cities, as: São Paulo (2008), Belo Horizonte (2010; 2016), Salvador (2010) and Curitiba (2012), by using different methodologies, during both data collection and statistical treatment stages. Considering the need to standardize the calibration methods, the aim of this work is to present the results of these calibrations, to compare them and to analyze the methodologies used in each calibration process, pointing out specific details of them. It is expected to come up with recommendations to forthcoming calibrations, making it possible to compare results and to facilitate future applications of the PET index as an evaluation tool for assessing thermal conditions in urban planning projects.

**Keywords:** Outdoor thermal comfort, PET index, thermal sensation, calibration methods

### Introduction

The design of open spaces in cities can contribute to stimulate the use of these areas, which additionally could provide a better quality of life for the population. In order to suitably plan these spaces, an important aspect to account is the outdoor thermal condition. It includes the consideration of the climate of cities, but also an evaluation of the different microclimate related to the different urban structures, which can influence the thermal comfort in open spaces. Besides, it is important to regard the human being as a reference.

However, the lack of information on the subjective perception and evaluation of comfort conditions in outdoor spaces makes it difficult to support planners in their decision-making (Nikolopoulou & Lykoudis, 2006). In this context, one way to contribute is by using outdoor thermal comfort indices, which integrate thermophysiological and subjective

parameters allowing the estimation of the thermal environment from a human approach. The Physiological Equivalent Temperature index (PET) is one of them and it is widely applied in the evaluation of outdoor thermal conditions.

PET ( $^{\circ}\text{C}$ ) is an index used to describe the thermal situation of a person, combining climatic parameters (mean radiant temperature, air temperature, wind speed and relative humidity), person's activity and type of clothing (Höppe, 1999). Furthermore, there are evidences that psychological processes based on sociocultural processes can influence the evaluation of a place in terms of thermal, emotional and perceptive aspects (Knez & Thorsson, 2006). Available choice, environmental stimulation, thermal history, memory effect and expectations also play an important role in the subjective evaluation of the microclimate conditions (Nikolopoulou et al., 2001). Considering the influence of all these parameters, the comfortable thermal conditions are not the same worldwide. Classes of thermal perception, including the comfort zone, can differ according to the local climate because people are adapted to different climatic conditions. Therefore, it is important to calibrate the index to each different place and culture, also considering these psychological processes.

The PET calibration process aims to determine representative intervals of thermal comfort conditions in order to predict thermal sensation according to an assessment scale. For this, two types of data are collected simultaneously: microclimatic parameters (air temperature, relative humidity, mean radiant temperature and wind velocity, obtained from meteorological measurements according to ISO 7726) and subjective thermal perception responses of acclimatized pedestrians, obtained from structured interviews. A scale of seven-point categories is normally used: +3 (Hot); +2 (Warm); +1 (Slightly Warm); 0 (Comfortable); -1 (Slightly Cool); -2 (Cool) and -3 (Cold) (ISO 10551).

In Brazil, due to its territory extension and climatic diversity, differences between the cities and their population must be considered when analyzing thermal comfort and thermal sensations in open spaces. According to the national technical standard NBR 15220-3 (ABNT, 2005), the country is divided into eight zones relatively homogeneous as to their climatic type. This emphasize the relevance and the need to consider the specific climatic and microclimatic conditions of each place together with the acclimatization process of the local population in order to get to know the specific thermal comfort zones of each locality.

Guided by the search of this knowledge, Brazilian researchers are performing calibrations of the PET index for urban spaces. They had already done it for four cities: São Paulo (Monteiro, 2008), Belo Horizonte (Hirashima, 2010; Hirashima, 2016 et al.; Hirashima, Assis, Nikolopoulou, 2016), Salvador (Souza, 2010) and Curitiba (Rossi, 2012). However, the studies adopted different methodologies in the calibration process, which make it difficult to compare the results and to apply them with planning purposes. In this context, this study aimed to analyze the methodologies already used in Brazil, to show the results of these calibrations, to compare them and to show their singularities. The standardization of the calibration method, at a national level, is an important tool to obtain comparable thermal comfort zones, which can be used in the prediction of thermal perception of the population. This will help in obtaining a more accurate assessment of the urban microclimates, and will contribute to a deeper understanding of issues related to urban thermal comfort in the different Brazilian climatic zones.

## Study areas

The PET index calibrations were carried out in four Brazilian cities: Belo Horizonte, Curitiba, Salvador and São Paulo. Table 1 shows some information about location, population and climatic classifications (based on Köppen and on climatic Brazilian zones) of each of these cities. Belo Horizonte and São Paulo are located in the southeast and are classified in the same climatic zone according to ABNT (2005), however the cities differ in terms of temperatures and wind speed – São Paulo has lower temperatures and higher wind speed. Curitiba is the southernmost city among the studied cities. It presents the least mean and minimum temperatures and the highest temperature amplitude. São Paulo is the most populous city, while Curitiba has the smallest population. Salvador is situated in the northeast of the country and it is the only city located on the coast. It has the highest values of mean temperature, relative humidity and wind speed (Table 2).

Table 1. Summary of information of the cities.

City	Location	Population (IBGE, 2010)	Köppen classification	Climatic zone (ABNT, 2005)
Belo Horizonte	19°49'S, 43°57'W	2,375,151	Aw / Cwa	3
Curitiba	25°25'S, 49°16'W	1,751,907	Cfb	1
Salvador	12°58'S, 38°30'W	2,675,656	Af	8
São Paulo	23°32'S, 46°38'W	11,253,503	Cwa	3

Table 2. Climatological data of each site (period from 1961 to 1990)<sup>1</sup>: mean temperature (Tm), minimum temperature (Tmin), maximum temperature (Tmax), relative humidity (RH) and wind speed (W). The elevation corresponds to the meteorological stations.

City	Elevation (m)	Tm (°C)	Tmin (°C)	Tmax (°C)	RH (%)	W (m/s)
Belo Horizonte	915,0	21.1	16.7	27.1	72.2	1.52
Curitiba	923,5	16.8	12.5	23.1	80.7	2.27
Salvador	51,4	25.3	22.7	28.2	80.9	2.28
São Paulo	792,1	19.2	15.5	24.9	78.4	2.67

<sup>1</sup>INMET, 2009

## Calibration of the PET index in Brazil: comparison of methodologies

In Brazil, the PET index has already been calibrated by applying different methods of collection and statistical treatment of data . In the calibration processes, during the data collection stage, measurements of microclimatic variables are conducted simultaneously with the application of questionnaires. These questionnaires are used to collect individual and subjective variables regarding thermal perception. Differences are evident in the sample size, target population, time and number of days in which the data collection occurred, study areas and measurement point definition, and so on.

Table 3 presents a summary of information about the methodologies used in the data collection stage of the PET calibration studies. It shows that the data collection procedures differ in most of the aspects considered, but they still have some similarities. The method used in Belo Horizonte in the years of 2009/2010 and in Salvador were almost the same, because these studies took part in the same research project. The only difference between them is the time of day in which field surveys were carried out. The calibration process used in São Paulo, on the other hand, is quite different from the others, because it was carried

out in the Campus of the São Paulo University (USP). Therefore, the location of the measurement points are particular and the students were the target population.

Table 3. Summary of PET calibration studies.

City	Number of interviews	Age of interviewers	Number of days	Sites of interviews	Time of the day	Measurement places	Year
Belo Horizonte <sup>1</sup>	944	20 to 59	8	2 squares	morning and afternoon	2 points (sun and shadow)	2009/2010
Belo Horizonte <sup>2</sup>	1,182	20 to 59	10	2 squares	morning and afternoon	2 points (sun and shadow)	2009/2010
Belo Horizonte <sup>3</sup>	1,690	20 to 59	4	2 squares	morning and afternoon	2 points (sun and shadow)	2013
Curitiba	1,685	13 to 91	15	15 points along streets	morning and afternoon	2 points (not specified)	2009/2010
Salvador	1,002	20 to 59	8	2 squares	afternoon	2 points (sun and shadow)	2009/2010
São Paulo	1,800	not specified	4	3 points in the University Campus	morning	3 points (1 in the sun, 1 bellow trees, 1 bellow a tensile cover)	2005/2006

<sup>1</sup> Hirashima, 2010.

<sup>2</sup> Hirashima et al., 2016.

<sup>3</sup> Hirashima, Assis, Nikolopoulou, 2016.

The number of valid interviews is different between each study, but they do not have a correspondence with the population size. For Belo Horizonte, the PET index has been calibrated three times. The results of 2010 considered a sample of 944 interviewees, but winter temperatures were higher than expected for this season, making it impossible to measure low temperatures. Hirashima et al. (2016) extended the sample used in 2010 by Hirashima (2010), totaling 1,182 interviewees, by carrying out one more field survey in the subsequent winter. Hirashima, Assis, Nikolopoulou (2016) performed a new and more recent study, with a sample of 1,690 interviewees. In this latter calibration, a larger sample and a wider range of microclimatic data, especially in cold thermal conditions were considered. The total number of valid interviews, defined by sampling processes, conducted in the other cities was: 1,800 in São Paulo; 1,002 in Salvador and 1,685 in Curitiba

All the surveys were carried out only during daytime and it is possibly not representative of the range of temperatures that can occur in each city. The point in which measurement equipment was placed is another aspect to be observed. In the case of the study carried out in Curitiba, the place of measurement was not specified, but it is

important that the place where the measurements are carried out be linked to the place where the interviews are done. In this city, the age of the interviewees diverges from the sample of Belo Horizonte and Salvador and this could have an impact on calibration due to the different thermal perception of young and old people.

Besides standardized, it is of ultimate relevance that, when more than one equipment is being used, it is important to certify that their measures are the same and the equipment used is also gauged between them. This detail, in fact, is shown in the works.

Some details such as the method used to calculate the values of the PET index are hardly mentioned in the studies. About it, Hirashima (2010) presented a comparison of two methods of calculation of PET values: a) using the software Rayman 1.2®, which applies specific data for each individual of the sample, and b) using the software developed by the University of Freiburg, the version of Holst (2007), applying default personal data. She concluded that the values generated by these two softwares, in this case, differ little. However it shows that it is important to demonstrate how it is calculated.

Considering the methodologies applied, in all studies, after data collection, the calculated value of the PET index is then related to the thermal sensation categories in a seven-point scale, ranging from hot to cold, with a neutral comfortable range. Statistical processes used normally adopt these two variables: the dependent variable, that is the thermal perception, a categorical variable with seven categories; and the independent variable, that is the PET Index, a continuous numeric variable.

At this stage, data can either be analyzed by each of the categories considered in the forms, or be recategorized. Regarding the precise definition of all categories of thermal comfort as considered in the seven-point scale (ISO 10551), the studies of Hirashima (2010), Hirashima et al. (2016) and Souza (2010) found that the small seasonal and diurnal thermal variation together with the prevailing thermal stress due to the hot conditions throughout the year have a great influence on thermal perception of acclimatized people. It is assumed that this situation could mask thermal perception, making it difficult to determine precise ranges for all the categories, specially for "slightly warm" and for all the categories related to cold thermal conditions ("slightly cool", "cool" and "cold"). Although the different climatic zones of Belo Horizonte and Salvador, both Hirashima (2010) and Souza (2010) did not manage to delimit "slightly warm". This was one reason why Hirashima, Assis and Nikolopoulou (2016) considered only the three categories presented ("cold", "comfort" and "hot"), in order to better define the ranges. Rossi (2012) also used only 3 categories in her results. Both Hirashima (2010) and Souza (2010) did not manage to delimit categories related to cold conditions, due to the lack of climatic data measured in this thermal condition.

The statistical methods used to determine the thermal comfort ranges in the cited studies were: iterative method (Monteiro, 2008), ordinal logistic regression (Hirashima, 2010; Hirashima et al., 2016; Hirashima, Assis, Nikolopoulou, 2016), decision tree (Souza, 2010) and Linear Discriminant Function (Rossi, 2012). The complexity and the great number of variables involved in human thermal comfort evaluation of urban environments require the use of multivariate data analysis for interpreting field research results. The methods ordinal logistic regression, decision tree and linear discriminant function are suitable multivariate techniques. However, further studies are still necessary to point out the most suitable multivariate technique must be used in the statistical treatment.

## Results of the calibrations

The results of the calibrations for the Brazilian cities mentioned above are presented in the Table 4:

Table 4. Results of PET calibrations. The values of the categories are expressed in °C of PET.

References / City	Categories						
	+3	+2	+1	0	-1	-2	-3
	Hot	Warm	Slightly warm	Comfortable	Slightly cool	Cool	Cold
Belo Horizonte <sup>1</sup>	>35	31 - 35		<30			
Belo Horizonte <sup>2</sup>	>36	32 - 35	31	16 - 30	13 - 15	<12	-
Belo Horizonte <sup>3</sup>	-	-	>27	19 - 27	<19	-	-
Curitiba	-	-	>23	18 - 23	<18	-	-
Salvador	>34	29 - 34	27 - 29	<27	-	-	-
São Paulo	>43	>31	>26	18 - 26	<18	<12	<4

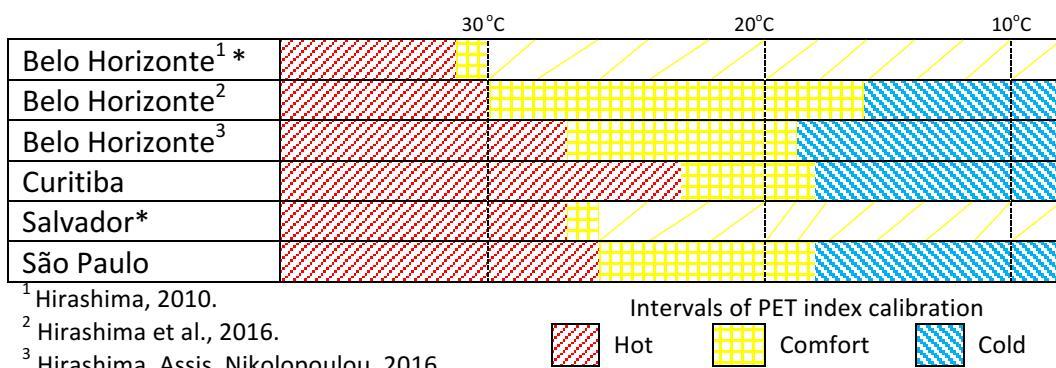
<sup>1</sup> Hirashima, 2010.

<sup>2</sup> Hirashima et al., 2016.

<sup>3</sup> Hirashima, Assis, Nikolopoulou, 2016.

The calibration results presented in Table 4 shows that the comfortable ranges established by Monteiro (2008) and Hirashima, Assis, Nikolopoulou (2016) are quite similar, presenting equal amplitude. These ranges were established to São Paulo and to Belo Horizonte, respectively, cities located in the same climatic zones. The ranges defined by Souza (2010) are shifted to warmer thermal conditions, when comparing to the other results. This may be attributed to the warmer thermal conditions characteristic of Salvador climatic zone. The comfortable band narrowing which can be observed in the study carried out by Rossi (2012) to Curitiba may also be related to the city climatic zone.

Figure 1 shows the results of the five calibration synthesized in three categories: hot (which includes "slightly warm", "warm" and "hot"), comfort and cold (which includes "slightly cool", "cool" and "cold"). The common range of comfort for all calibrations was between 19 and 23°C. Above 31°C, all of them are categorized as hot. In Belo Horizonte<sup>1</sup> and Salvador, the limit for the cold category was not found. In the other researches, the superior limit for this category is 16 °C.



<sup>1</sup> Hirashima, 2010.

<sup>2</sup> Hirashima et al., 2016.

<sup>3</sup> Hirashima, Assis, Nikolopoulou, 2016.

Figure 1. Synthesis of PET index calibrations in three intervals. In the calibrations marked with (\*), the inferior limit of the comfort category was not determined.

## Conclusion

This paper presented different methodologies used in Brazil in order to calibrate the PET index for the local population and their results for the cities of Belo Horizonte, Curitiba, Salvador e São Paulo. The results show that the methodologies used in the cited studies are effective and valid, presenting their singularities. Differences in climatic zones show differences in ranges of PET values that must be better investigated. The lack of information of some processes during the calibrations and the different methods used to do them make it difficult to compare the results.

This study can be configured as a guide that can conduce to an in-depth discussion, generating subsidies to future contributions in this field. The possibility of combining the presented methodologies represents an opportunity to explore and to enhance the study of the subject. However, this work also indicates that further studies should be carried out in order to evaluate the pertinence of using a symmetrical two-pole 3 or 5 point-scale in the assessment of the perception of thermal conditions in open urban spaces in Brazil, due to the tropical climate features, which is characterized by a small seasonal and diurnal variance in thermal conditions, presented in a large part of this country.

Considering the standardization of the calibration process, this work suggests that future studies should be carried out in order to define which specific methodological and statistical procedures should be used in the calibration of thermal indexes for urban spaces in Brazil, making it possible to compare thermal comfort zones in different cities, to predict thermal sensations of their population and to better assess their urban microclimates. We hope this will positively contribute to the suitable planning of open spaces in Brazilian cities, improving outdoor thermal conditions.

## References

- ABNT NBR 15220-3 (2005). *Desempenho térmico de edificações - Parte 3: Zoneamento bioclimático brasileiro e diretrizes construtivas para habitações unifamiliares de interesse social*. Rio de Janeiro: Associação Brasileira de Normas Técnicas.
- Abreu, M. N. S., Siqueira, A. L., Caiaffa, W. T. (2009). Regressão logística ordinal em estudos epidemiológicos. *Rev. Saúde Pública*, 43(1), pp. 183-94.
- Andrade, T., Nery, J., Moura, T., Miranda, S., Pitombo, C., Katzschner, L. (2015). PET Comfort Index Calibration Using Decision Trees. In: WMO, Météo-France, IAUC, AMS, 9th International Conference on Urban Climate jointly with 12th Symposium on the Urban Environment. Toulouse, 20 - 24 July 2015. Toulouse: Météo-France.
- Hirashima, S. Q. S. (2010). *Calibração do índice de conforto térmico temperatura fisiológica equivalente (PET) para o município de Belo Horizonte, MG*. Msc. Universidade Federal de Minas Gerais.
- Hirashima, S. Q. S. (2014). *Percepção sonora e térmica e avaliação de conforto em espaços urbanos abertos do município de Belo Horizonte - MG, Brasil*. Phd. Universidade de São Paulo.
- Hirashima, S. Q. S., Assis, E. S., Nikolopoulou, M. (2016). Daytime thermal comfort in urban spaces: A field study in Brazil. *Building and Environment*, 107, pp. 245-253.
- Hirashima, S. Q. S., Katzschner, A., Ferreira, D. G., Assis, E. S., Katzschner, L. (2016). Thermal comfort comparison and evaluation in different climates. *Urban Climate* (In Press).
- Holst, J. (2007). Physiological Equivalent Temperature (calculation based on MEMI) [software]. Freiburg: Albert-Ludwigs-Universität Freiburg.
- Höppe, P. (1999). The physiological equivalent temperature PET – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43, pp. 71-75.
- IBGE - Instituto Brasileiro de Geografia e Estatística (2010). População: Censo 2010. Available in <<http://www.cidades.ibge.gov.br>>. Access in March 20, 2017.

INMET - Instituto Nacional de Meteorologia (2009). Normais climatológicas do Brasil: 1961-1990. Brasília: INMET.

ISO 7726 (1998). *Ergonomics of the thermal environment - Instruments for measuring physical quantities*. Genève: International Organization for Standardization.

ISO 10551 (1995). *Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgment scales*. Genève: International Organization for Standardization.

Knez, I., Thorsson, S. (2006). Influences of culture and environmental attitude on thermal, emotional, and perceptual evaluations of a public square. *International Journal of Biometeorology*, 50, pp. 258-268.

Monteiro, L. M. (2008). *Modelos preditivos de conforto térmico: quantificação de relações entre variáveis microclimáticas e de sensação térmica para avaliação em projeto de espaços abertos*. Phd. Universidade de São Paulo.

Nikolopoulou, M., Baker, N., Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy*, 70 (3), pp. 227-235.

Nikolopoulou, M., Lykoudis, Spyros (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41, pp. 1455-1470.

RayMan 1.2 (2000). Free software. Developed by Matzarakis, A., Mayer, H. Freiburg: Meteorological Institute of the University of Freiburg. Available in: <[www.urbancimate.net/rayman](http://www.urbancimate.net/rayman)>. Access in September 23, 2009.

Rossi, F. A. (2012). *Proposição de metodologia e de modelo preditivo para avaliação da sensação térmica em espaços abertos em Curitiba*. Phd. Universidade Tecnológica Federal do Paraná.

Souza, S. H. M. (2010). *Avaliação do desempenho térmico nos microclimas das praças: Piedade e Visconde de Cayrú, Salvador, BA*. Msc. Universidade Federal da Bahia.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Retrofit of Mangaldas Market considering Indoor Environment Quality

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**Abstract:** Indoor environmental quality and well being of occupants is an important parameter to evaluate naturally ventilated buildings. In this study thermal comfort, air quality, Lux levels in day and night time are analysed for Mangaldas Market. The aim was to evaluate thermal and visual discomfort, and air quality ( $\text{CO}_2$  level) in market, study their cause and suggest strategies to improve thermal comfort and air quality, and in the process reducing the use of artificial lights at the Market. The methodology of study to evaluate environmental parameters of thermal comfort and Air quality ( $\text{CO}_2$  level), was through on-site measurements using Awair IEQ sensor along with comfort survey of visitors and vendors through questionnaire, and field observations. It was found that the change in occupancy pattern reflects change in  $\text{CO}_2$  levels.  $\text{CO}_2$  levels measured inside the market were in the range 1500 ppm resulting in higher  $\text{CO}_2$  levels for maximum duration. Indoor temperature observed  $15^{\circ}\text{C}$  above the comfort range. The air movement in the market was minimal resulting in poor or no natural ventilation. Low WWR and SSR resulted in lack of daylight which resulted maximum use of artificial lights, adding to heat gain.

**Keywords:** Indoor Market, thermal comfort, Air Quality, Occupants

### Introduction

Built environment and comfort is closely associated and combination of both creates acceptable thermal environment conditions for the occupants. The quality of the indoor environment reflects on the health, comfort and productivity of occupants (J, 2004). It includes aspects of indoor air quality, thermal comfort, acoustic quality, and lighting quality. This study gathers to generate qualitative and quantitative data about the comfort parameter and indoor environment quality for vendors and visitors at Mangaldas Market. The aim of the study is to recommend strategies to improve thermal comfort, visual comfort and air quality ( $\text{CO}_2$ ) at Mangaldas Market.

The objective of the study was to analyse thermal, visual comfort parameters;  $\text{CO}_2$ , levels in Mangaldas Market through on site measurements and comfort survey also, arriving at reasons for thermal discomfort, visual discomfort; and high  $\text{CO}_2$  levels and to suggest guidelines to improve visual comfort, improve thermal comfort and to decrease  $\text{CO}_2$  level Mangaldas market.

Mangaldas Market, traditionally a home to traders from Gujarat, considered as the Mumbai's heritage cloth Market. Hundreds of vendors sell a colourful array of textiles inside the market. Market runs for 8hrs. The market is filled with over 600 shops along its central lanes and nine lanes that intersect one another. The existing Mangaldas Market is an enclosed (indoor), single story structure, building facade has few openings with very low WWR and SRR. Though occupancy of market differs according to seasons and for shopping and day timings, the market is crowded for entire day.

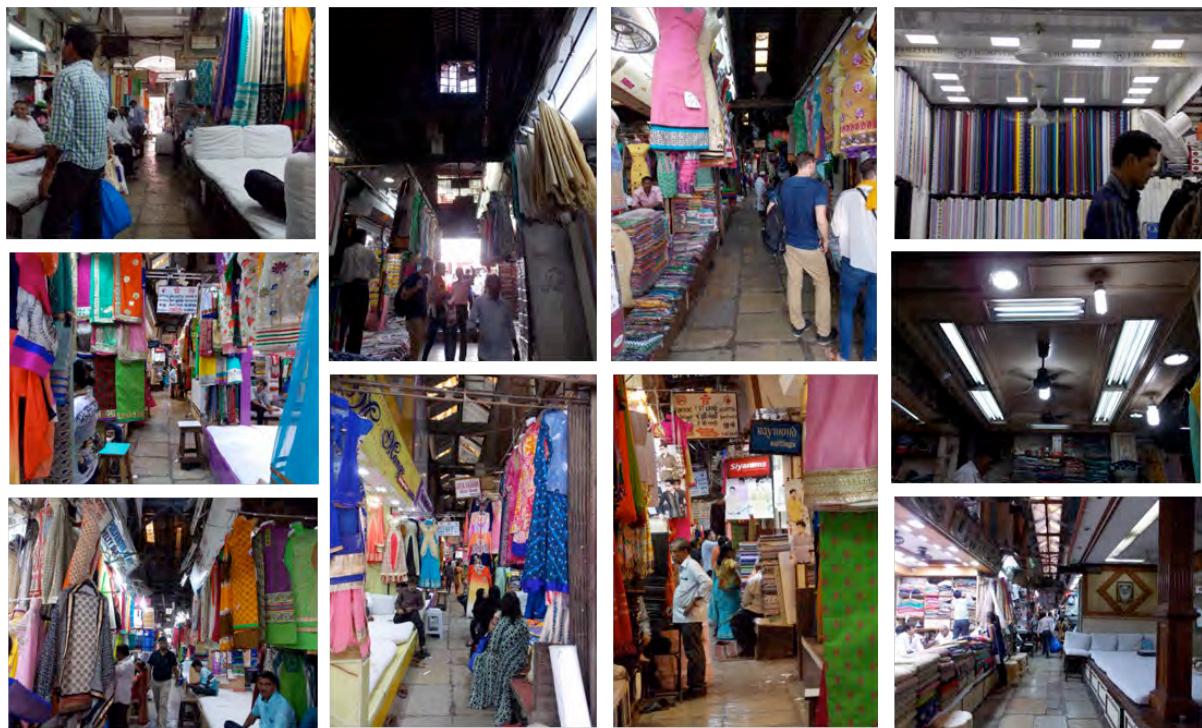


Figure 1. Mangaldas Market

## Methodology

The methodology obtained for this study was divided into three stages, such as 1) On site data collection, 2) Comfort survey of visitors and vendors, 3) On site observations. The study was conducted in the month of March, 2016 for five days.

Purpose of the onsite measurement was to analysed parameters of thermal comfort such as Dry Bulb Temperature, Relative Humidity and Air movement. Dry bulb temperature and Relative humidity was measured hourly inside the market at three different nodes. Ambient dry bulb temperature and R. humidity was also measured outside the market to analyse the difference between outside environment and inside environment. Air movement was measured hourly at all the entrances of Mangaldas market. CO<sub>2</sub> level inside the market was measured at three different nodes and also outside the market. The lux level was measured at 24 different nodes.

The comfort survey of vendors and visitors was carried out to understand their thermal comfort as vendors spend around 33% of a day inside the market. Also the comfort survey helped to understand the annual occupancy of visitors inside the market. The sample for comfort survey was selected by random sample method. Comfort Survey was carried out along with on site measurements. The comfort survey was performed for every hour considering three vendors and three visitors to analyse the activities and thermal comfort.

The observations were performed to understand the hourly occupancy pattern of visitors, activities of vendors and market, clothing pattern of vendors. The occupancy of visitors was measured at 24 different nodes to understand the density pattern.

## Data Analysis

Hourly readings of Dry Bulb Temperature, Relative Humidity, CO<sub>2</sub> levels further analysed with occupancy patterns and ASHRAE Standards, National Building Codes, Indian Model of thermal Comfort to understand the thermal comfort of visitors and vendors.

### *Occupancy*

Observation concluded that the (Figure 2) maximum footfall of visitors was observed between 16 to 19 hrs, 1104 visitors/hour which was 53% higher. It was observed that the density of footfall varied as per weekdays and weekdays. The footfall observed on Saturday was approximately 10,452 which were 16% more than weekdays and 47% more than Sunday. From observation it was conclude that the density of visitors varied as per the different location with maximum density of 42 visitors/Hour/Sqm and to minimum 27 visitors / hour/ Sqm.

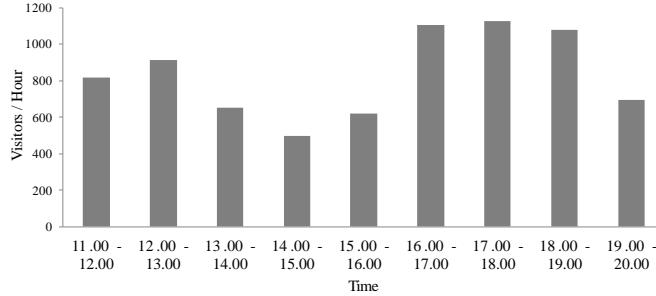


Figure 2. Hourly occupancy patterns

### *Dry Bulb Temperature*

The average indoor temperature measured inside the market was in the range of 30<sup>0</sup>C to 32<sup>0</sup>C between 11hrs to 15 hrs. after 15 hrs it was measured above 33<sup>0</sup>C. It was observed that (Figure 3) the indoor temperature was constantly higher compared to the ambient temperature, the difference observed was between the ranges of 2<sup>0</sup>C to 6<sup>0</sup>C. After 19 hrs when ambient temperature drops down to 30<sup>0</sup>C, the indoor temperature remains constant in the range above 34<sup>0</sup>C.

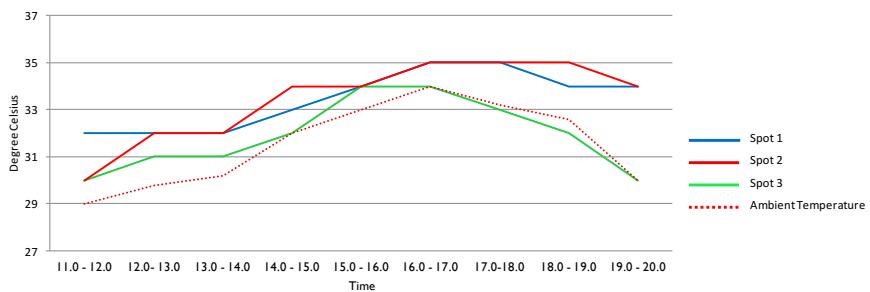


Figure 3. Dry Bulb Temperature

The range of effective indoor temperature for Mangaldas Market was derived considering ambient temperature (Table 1). As per ASHRAE Standard 55, the effective indoor temperature was in the range of 27<sup>0</sup>C. According National Building Codes it's in the range of 29<sup>0</sup>C to 30<sup>0</sup>C. The Indian model for adaptive comfort provides the range of Indoor temperature in the range of 20<sup>0</sup>C to 28<sup>0</sup>C for Hot and Humid climate of Mumbai. When the

indoor temperature compared with the effective indoor temperature (Figure 4) it confirmed that the indoor temperature noted inside the Mangaldas Market was above the range of effective indoor temperature ( $T_{Com}$ ) which needs to reduce by an average  $15^{\circ}\text{C}$  to achieve required effective indoor temperature and thermal comfort inside the market.

ASHRAE Standard 55 : Effective Indoor temperature ( $T_{Com}$ ) =  $0.31 \times T_{\text{ambient}} + 17.8^{\circ}\text{C}$   
 National Building Codes: Effective Indoor temperature ( $T_{Com}$ ) =  $0.54 \times T_{\text{ambient}} + 12.83^{\circ}\text{C}$

Table 1. Indoor Dry Bulb Temperature – Ambient Dry bulb Temperature - Effective Indoor Temperature

Time	Mean ambient temperature for five days ( deg C )	Mean indoor temperature for five days ( deg C )	Avg Diffrance (deg C)	Adaptive Comfort Standards	National Building Codes	Indian Model for Adaptive Comfort (IMAC)
				$T_{Com} = 0.31 \times T_{\text{a}} + 17.8$	$OT = (0.54 \times OT) + 12.83$	(20.5 to 28.5)
11.00 - 12.00	30.44	32.16	1.7	27.23	29.26	24
12.00 - 13.00	30.84	32.86	2	27.36	29.48	24
13.00 - 14.00	31.3	33.86	2.5	27.5	29.73	24
14.00 - 15.00	32.24	34.6	2.3	27.79	30.23	24
15.00 - 16.00	33.54	35.22	1.68	28.19	30.94	24
16.00 - 17.00	34.12	35.52	1.4	28.37	31.25	24
17.00 - 18.00	33.26	35.4	2.1	28.11	30.79	24
18.00 - 19.00	32.4	35.02	2.62	27.84	30.32	24
19.00 - 20.00	30.32	34.66	4.34	27.19	29.2	24

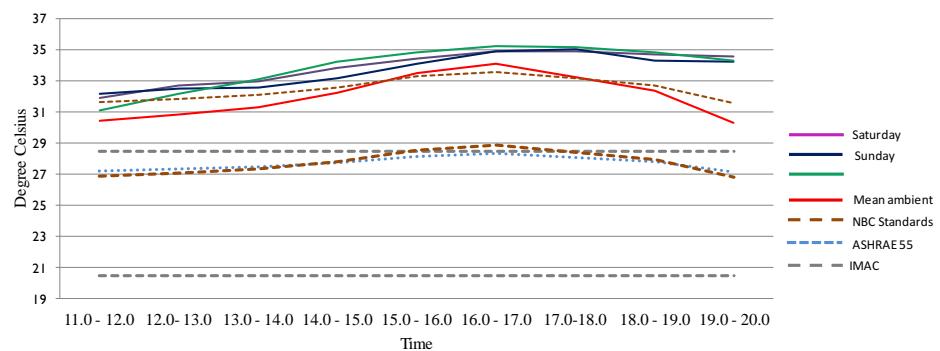


Figure 4. Indoor Dry Bulb Temperature - Ambient Dry bulb Temperature - Effective Indoor Temperature.

### Air movement

The Air movement measured at Mangaldas Market was in the range of 0.2 m/s to 0.8 m / s . It was observed that after 15 hrs the air movement measured was very low below 0.2 m / s. For effective indoor temperature between  $27^{\circ}\text{C}$  to  $30^{\circ}\text{C}$  the desirable air movement shall be between 0.6 m / s to 1.8 m / s. When indoor air movement was compared with the desired air movement (Figure 5) it was conclude that the existing air movement observed was very low which resulted into heat trap causing high indoor dry bulb temperature

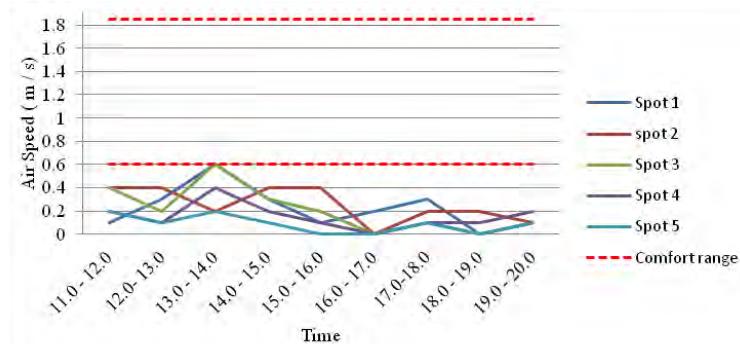


Figure 5. Air Movement m / s

### **Relative Humidity**

The Relative humidity measured at Mangaldas Market, was in the range of 46% to 35%. The psychometric chart below (Figure 6) concludes that the indoor Dry Bulb Temperature and Relative humidity at Mangaldas market was not sufficient to provide thermal comfort for all the 45 hrs hours analysed. It was observed that the hours analysed at Mangaldas Market was above the comfort range.

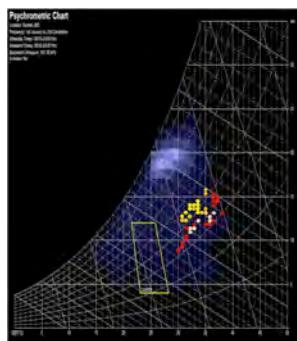


Figure 6.Psychometric chart

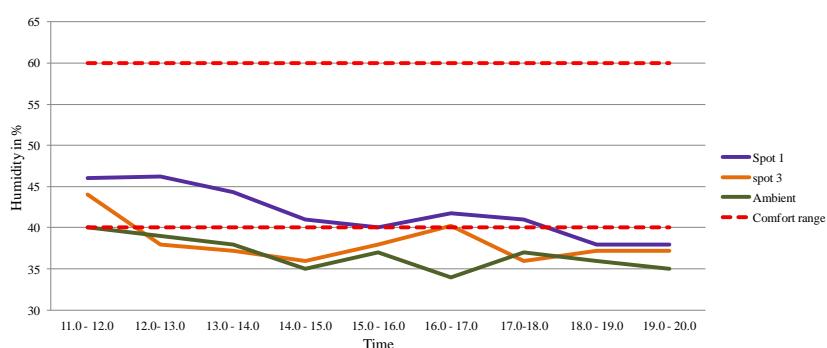


Figure. 7 Relative Humidity

### **Comfort Survey**

The comfort survey resulted that for most of the hours visitors were unsatisfied with thermal environment where as vendors were slightly comfortable for measured indoor dry bulb temperature and Relative Humidity. Comfort survey concludes that between 2 pm to 4 pm maximum visitors and vendors were unsatisfied with thermal environment.

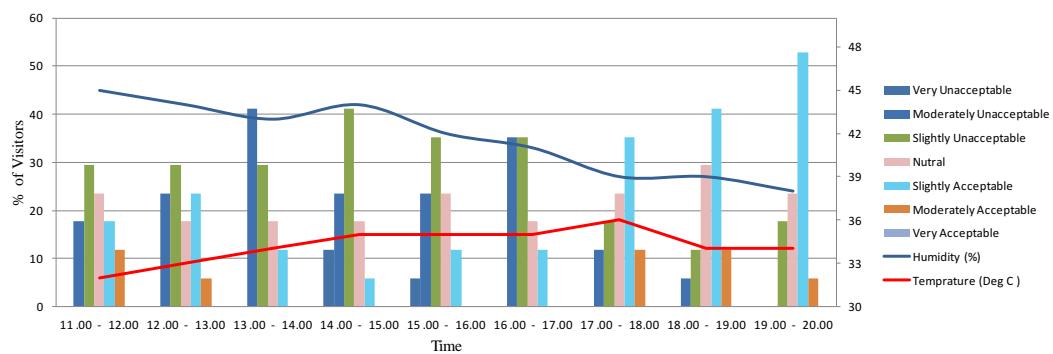


Figure.8 Comfort Survey – Vendors

### **CO<sub>2</sub> level**

It was observed that (Table 2) the CO<sub>2</sub> levels measured at Mangaldas Market was in the range of 350 ppm to 1800 ppm. The ambient CO<sub>2</sub> level observed was in the range of 300 ppm to 500 ppm.

When ambient and indoor CO<sub>2</sub> level was compared it was analysed that the difference observed in ambient and indoor CO<sub>2</sub> level varied as per time. Between 11 to 12 hrs when market was just started the difference observed was minimum 33 ppm which was 10 % higher than the ambient CO<sub>2</sub> level. Between 19 to 20 hrs. the difference observed was maximum 1227 ppm 44% higher than the ambient CO<sub>2</sub> level.

As per National Building Codes the indoor CO<sub>2</sub> level should not exceed more than 700 ppm compared to ambient CO<sub>2</sub> level and as per ASHRAE Standard 62.2 the indoor CO<sub>2</sub> level should not exceed more than 1000 ppm for well being of occupants.

In the graph below (Figure. 9) the indoor CO<sub>2</sub> levels was compared with the occupancy pattern. It was analysed that the between 4 to 7 pm when occupancy increased by 50 % it resulted into increase in CO<sub>2</sub> levels by 53% than that of CO<sub>2</sub> levels before 16hrs. It was conclude that (Table. 2 and Figure. 8) the CO<sub>2</sub> level at Mangaldas Market increased as the occupancy increased. It was concluded that (Table. 2) the indoor CO<sub>2</sub> level was higher for 5hrs which confirms that the vendors spend 63 % of time in higher CO<sub>2</sub> level when compared to total time spent at Mangaldas Market.

Table 2. Indoor CO<sub>2</sub> Level – Ambient CO<sub>2</sub> Levels – Effective CO<sub>2</sub> Levels

Time	Mean ambient CO <sub>2</sub> Level (PPM)	Mean indoor CO <sub>2</sub> Level (PPM)	Avg Diffrance (PPM)	ASHRAE standards (PPM)	NBC standards (PPM)
11.00 - 12.00	329	362	33	1000	1029
12.00 - 13.00	330	499	169	1000	1030
13.00 - 14.00	367	592	225	1000	1067
14.00 - 15.00	410	953	543	1000	1110
15.00 - 16.00	443	1039	596	1000	1143
16.00 - 17.00	550	1143	593	1000	1250
17.00 - 18.00	568	1440	872	1000	1268
18.00 - 19.00	500	1673	1173	1000	1200
19.00 - 20.00	539	1766	1227	1000	1239

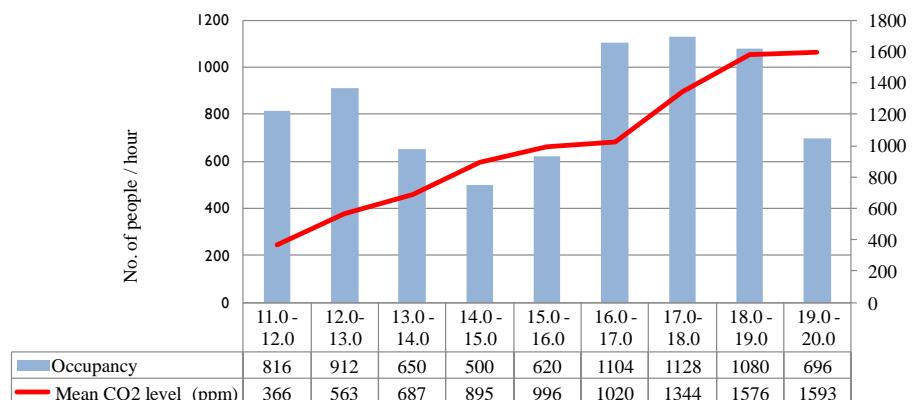


Figure 9. Indoor CO<sub>2</sub> level – Occupancy at Mangaldas Market

### Day-time and Night-time Lux Levels

The existing window to wall ratio calculated at Mangaldas Market was 5% and Skylight to roof ratio calculated was 4%. The existing skylights and openings allow infiltrating of daylight on 30% of floor area of Mangaldas Market which acted as daylight lid area. It was observed that the roof of indoor shops acted as obstacles which resulted into reduction of daylight lid area by 20% inside Mangaldas Market. Mood light was provided to concur the absence of daylight. The day time Lux level and Night time level measured at Mangaldas market was in the range of 300 lux to 1500 lux.

### Key Findings

The indoor temperature observed at Mangaldas Market was in the higher range, which needs to reduce by 15°C to achieve thermal comfort at Mangaldas Market. Building envelope and roof is exposed to Sun hence transfers heat inside market which heats up the market. Low openings causes less natural ventilation causing heat trap resulting higher indoor temperature. Further, when footfall of Visitors reaches to the maximum low natural ventilation causes higher CO<sub>2</sub> levels which give the sense of suffocation. Absence of daylight concurred by using artificial lights which add ups into heat gain.

It was analysed with Psychometric Chart that no other strategy is effective for passive comfort except Shading & Ventilation when the comfort parameters were set at  $22^{\circ}\text{C}$  to  $26^{\circ}\text{C}$  for dry bulb temperature & relative humidity to 60%.

## Design recommendations

### *Proposing openings to the building envelope*

Existing window to wall ratio is insufficient to have desired ventilation hence the existing openings with 1m diameter above entrances of the Market shall be replaced with openings along the length of wall for every facade. It was observed that the existing shops along the periphery of the external wall restricts position of openings also existing wall above the shops acts as a dead facade hence the new openings are proposed above 2.5M from the finished floor level in order to achieve daylight and induced ventilation. With the proposed redesign of the envelope existing window to wall ratio is changes from 5 to 24.

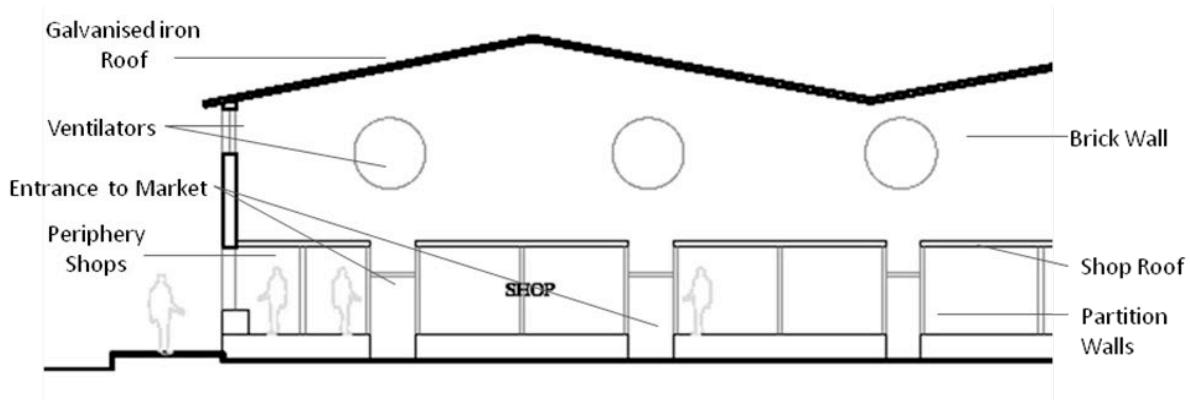


Figure 20. Existing Mangaldas Market



Figure 31. Proposed strategies for Mangaldas Market

### *Proposing skylights on the roof of Market*

Existing layout of Mangaldas market allows openings only on external wall. It was observed that daylight penetrating from building envelope was not able to reach in the interior of Market, which is filled with shops with their own roofs and wooden partition wall and passages along the market. which causes use of artificial lights resulting into heat gain. Also the periphery shops restrict the size and position of the openings. Hence skylight shall be proposed over galvanised iron roof which runs through entire market in order to increase the daylight lid area. The proposed skylight to roof ratio changed from 4 to 12 in order to penetrate more daylight in the interior of market.

### *Mutual Shading*

Existing building envelope does not contain shading devices hence all facades are exposed to solar radiation and acts as a medium of heat transfer inside the Market. The incident solar ingestion shall be reduced by proposing shading devices on proposed openings. 750 mm wide shading devices will help to create mutual shading which will help to reduce solar ingestion.

### ***Solar reflector paints in interiors of the Market***

Existing roof and wooden partitions of shops inside the Market acts as an obstacle for daylight to reach up to passage inside the market, which reduces daylight lid area by 20% hence in order to increase the infiltration of daylight inside the market interior of shops, roofs and wooden partition shall be treated with application of solar reflective paints which will act as a reflector and help to penetrate maximum daylight inside the Market.

### ***Absorption of solar radiation on roof***

Existing galvanised iron roof which is permanent source of heat transfer shall be treated with high albedo paint in order to reduce heat gain. It was analysed that because of majors like high albedo paint on roof there is a considerable decrease of 36% in surface absorption resulting in reduction of heat gain.

### ***Mechanical Ventilation inside the Market***

It was analysed that the air movement measured inside the market was in the range of 2 to 8 m/s, which is insufficient and causes heat trap inside Market. Recommended air changes per hour (ACPH) for public place shall be 15 ACPH which can be achieved by providing mechanical ventilation at Mangaldas market. To avoid ambient pollutants inside the market positive pressure shall be maintained inside the market. This can be achieved by keeping exhaust CFM lesser than Fresh air supply CFM by 30%. To achieve thermal comfort, considering 15 ACPH 20,000 CFM of fresh air shall be supplied at Mangaldas market. The fresh air and exhaust air duct shall run above the passage of the Market.

## **References**

- Allad , F (1998). Natural Ventilation in building, A Design Handbook,1 – 7.
- ASHRAEStandard 55, (2005). The American Society of Heating, Refrigerating and Air Conditioning Engineers. United States of America: ASHRAE.
- Brager G. S. (2002). Thermal comfort in Naturally Ventilated Buildings revision to ASHRAE Standard 55, Energy and Building, 12 – 15.
- Chang M. (2000). Indoor and Outdoor air quality investigation at school in Hong Kong, Pergamon Journal, 2 – 5.
- D.S.Vissers (2002). The human body as its own sensor for thermal comfort, Department of built Environment Endhoven university of Technology Netherlands, 33 – 39.
- Givoni B. (1976). Man, Climate and Architecture, Applied Science Publishers, 18
- R.V. Smiha (2012). Thermal Comfort in India, GRIHA, India, 24-55
- Indraganti M. (2010). Adaptive use of natural ventilation for thermal comfort in Indian apartments, Building and environment, 17-19.
- J.S. (2004). On the history of Indoor air quality and health, Journal of indoor built environment.
- Mishra A. (2013). Field studies on human thermal comfort, An overview building and environment, 21
- National building codes (2005). Part 8 Building services Section 3 Air conditioning, Heating and Mechanical Ventilation, Bureau of Indian Standards: India.
- Oglay V. (1973). Design with climate, Princeton University Press, 14 – 26.
- Sundell J. (2004). On the history of indoor air quality and Health, Journal of Indoor built environment, 22
- Wong N.H. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore, Building and environment.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The Importance of Comfort Indicators in Home Renovations: a Merger of Energy Efficiency and Universal Design

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**Abstract:** Literature, governmental and policy goals reveal a need to merge the, until now separately considered, concepts of Universal Design (UD) and Energy Efficiency (EE) in home renovations. Using the concept of Comfort from the perspective of homeowners, as a framework that unifies UD and EE, a list of 21 comfort indicators was developed. This paper discusses a survey undertaken with 145 homeowners to check whether these comfort indicators were indeed important from a homeowner's perspective when building or renovating their home. It also looked at their relative importance and any possible interconnections between the indicators. In addition, the survey explored the triggers and goals of home renovations. The results show that the developed list of comfort indicators can be considered reasonably concise and complete. Comfort factors fall into 3 groups of importance with EE associated indicators located somewhere in the middle pack. This order does not significantly change between people who plan to build a new home, those who plan to renovate, and those who do not have concrete plans yet. The deeper understanding of indoor comfort indicators and their importance for homeowners supports our efforts to develop a user-focused synergistic merger of UD and EE under the umbrella of indoor environmental comfort in practice and research.

**Keywords:** comfort, indicators, home renovation, energy efficiency, universal design

### Introduction

Two governmental and policy goals - increasing energy efficiency in homes and increasing the ability of homes to accommodate people during their whole life - have been separately considered in practice and research until recently. The housing stock in Belgium consists of a high proportion of single family homes that are energy inefficient and unsuitable for people with disabilities (Van den Broeck, 2015). This context presents an opportunity to combine energy efficiency and universal design into renovation concepts that create more value for individual homeowners and society at large.

Merging the concepts of energy efficiency (EE) and Universal Design (UD) is however fraught with difficulties due to their very different nature (Kapedani, Herssens, & Verbeeck, 2016). In order to bridge these two fields and provide a better relation between the wider goals of policy makers and the more narrow and immediate goals of individual home owners, the concept of comfort has been employed. The meaning of comfort in the context of home renovations was explored through 3 qualitative studies with different groups (UD professionals, home owners, architecture students). It resulted in a framework describing indoor environmental comfort (IE Comfort) which includes aspects of both EE and UD (Kapedani, Herssens, & Verbeeck, Accepted).

The terms used by study participants to describe comfort in combination with literature on building quality assessment were refined into a list of 20 indicators of indoor environmental comfort. They include 4 EE related indicators (*air quality, temperature, noise, light*) and 16 spatial and design indicators for lifelong-living (LLL) such as *usability of spaces, flexibility, accessibility, etc.* (see Fig. 1 for full list of indicators).

It should be emphasized that although this specific definition of indoor environmental comfort is in large part derived from a layman's understanding of the term, it does not have the same meaning as the term "comfort" in common use. The latter can have a variety of intuitive and sometimes vague interpretations depending on personal, social and contextual factors. For the remainder of this paper "IE Comfort" is used to refer to the concept described above as an overarching combination of EE and LLL indicators, while the common usage is described simply as "comfort".

The framework and indicators for IE Comfort are useful for understanding the conceptual relationship between Energy Efficiency and Universal Design. However they are not yet validated. The question remains whether these IE Comfort indicators are indeed important to homeowners in the construction or renovation of their home and, if so, how they might be related to each other and to the triggers and goals for renovation. In order to address these questions a survey was undertaken, the results of which are discussed in the following paper.

## Methodology

The survey was administered in person either digitally or in paper form to 145 attendees at the Batibouw 2016 construction fair in Brussels. The Batibouw event was selected because it is generally frequented by our target group for the survey: people who are interested in undertaking new construction or renovation work on their homes.

The main goal of the survey was to understand the importance of IE Comfort indicators from the perspective of homeowners. Of particular interest was the importance of indicators relative to each other and their interconnections. Respondents were presented with one question asking to select which factors from the list were important in their new construction or renovation. To ensure the respondents had a similar understanding, each term was explained with a brief phrase. The word "comfort" was not mentioned in this specific question. Multiple choices were possible and the list was randomized in the digital version of the survey.

In addition, the reasons for renovation were explored. The initial reasons that catalyzed people to think about a renovation might evolve and include other aspects into the final scope of renovation. Therefore these are separated into *triggers*, the catalyst causes of renovation, and *goals*, the evolved objectives of the renovation. The triggers and goals were questioned separately. Our hypothesis was that comfort, in its intuitive interpretation, is a more important goal than energy efficiency, lifelong-living, or technical factors. The questions were asked only to respondents who indicated that they had plans to renovate. Multiple choices were possible.

In the analysis, descriptive statistics were used for ranking of IE comfort indicators, renovation triggers and goals. To understand which choices were significantly more chosen than another a two-proportion z-test was employed. Spearman rank correlation allowed the comparison of ranking order differences between respondent groups.

Crosstabs were used to test independence of two indicators. Due to the large number of IE comfort indicators a chi-square test for each combination could lead to a significant

number of false positives. Therefore a set of 37 (from a possible 210) combinations was selected for testing. First, combinations of indicators with the same level of importance were selected for testing. Then a few more combinations were selected based on reasonable hypothesis of correlation such as *Natural light* with *Views to outside* and *Privacy*.

### **Limitations**

This study is based on the hypothesis that the list of indicators assembled indeed represent comfort in the indoor environment. The definition of comfort is an elusive, complex, and contested subject, no less so in the fields of EE and UD. Our goal here is not to test this hypothesis, but instead to develop a practical understanding of aspects that are important from the perspective of homeowners in the construction or renovation of their home – aspects which are related to EE and UD and can be grouped under the umbrella concept of comfort.

The number of comfort indicators selected may have to do with people's cognitive load and attention span since it is difficult for people to concentrate or remember long lists of items.

The selective sampling of attendees in a construction fair means that our survey sample is not representative of the Flemish population (e.g. people under 40 are overrepresented), however it better represents a subgroup which is considering renovation or construction works. The size of the sample is often too small for deeper statistically significant analysis into the choices of sub-groups such as the elderly (over 60 years old, n=17).

## **Results**

### **Sample description**

The majority (59%) of respondents was under the age of 40 and 55% has a college or university degree. They fall into 3 roughly even groups when describing their construction plans as having no concrete plans yet (34%), planning to build a new home (31%), and planning to renovate their home (35%). 82% of those with concrete plans for new building or renovation was planning to be owner-occupiers, which is consistent with the very high rates (70% in 2013) of home ownership in Belgium (Van den Broeck, 2015).

Those respondents who had plans to build a new home are obliged by law to hire an architect. Renovators however are not always obliged and, when asked, only 44% of them involved the services of an architect in their renovation project.

The house elements that respondents planned to modify comprised mostly of work on the building envelope (insulation, windows and doors) and light interior renovations (bathrooms and kitchens, interior finishes, but no structural changes or walls moved).

### **Indoor Environmental Comfort indicators**

About half of the 145 respondents choose between 7 and 12 aspects that are of importance to them. Only 2 people are "single-issue" builders/renovators, and 3 people find 19 different indicators important. No-one selected more than 19 indicators (out of a list of 22, of which one was "other").

The chart in Figure 1 shows the percentage of respondents who selected each indicator as important to them. *Natural light* is the indicator that is important to the largest number of people (83%) while *Artificial light* is important to just over 12% of respondents.

A two-proportion z-test shows that the rest of the indicators fall into 3 groups of importance where the indicators within the group are statistically equal to each other

( $p>0.05$ ). These groups are also visually apparent and illustrated in Figure 1. The indicators *Elegance* and *Accessibility* can be considered as either part of the first group (since the difference between *Accessibility* and *Maintenance* is not statistically significant,  $p>0.05$ ) or the second group (since the difference between *Elegance* and *Noise* is not statistically significant).

Rank correlation was used to compare the order of importance for the people who were planning a new-built house ( $n=45$ ), those who were planning a renovation ( $n=50$ ), and those who had no concrete plans at the time ( $n=50$ ). The order of importance is very similar between the 3 groups (Spearman correlation coefficients between 0.84 and 0.87 with  $p<0.001$ ).

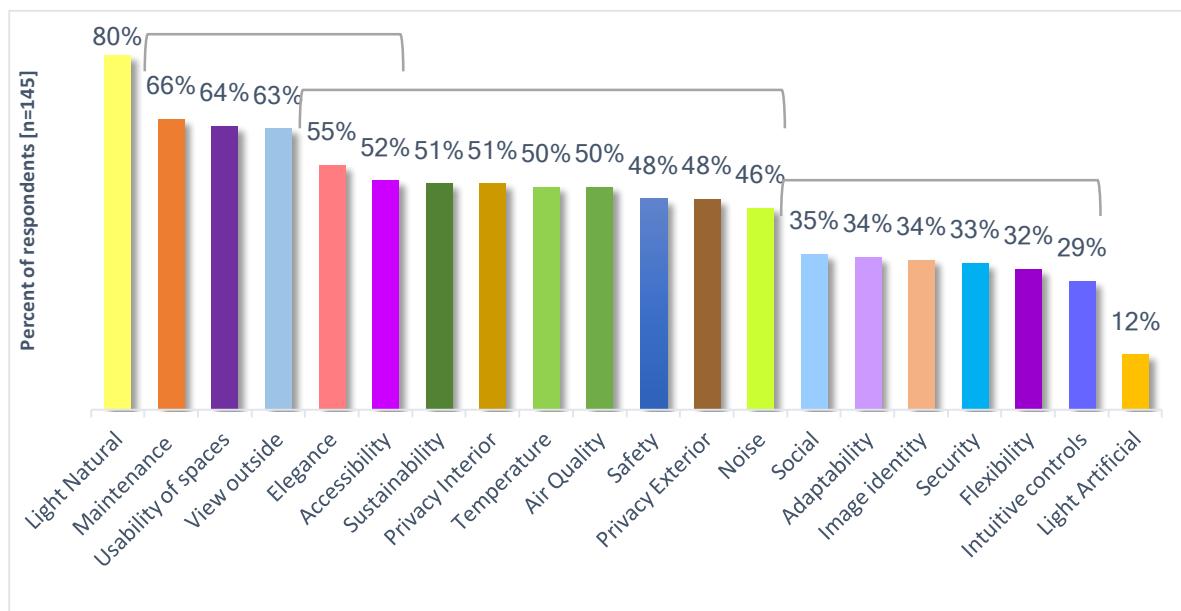


Figure 1. The proportion of respondents who selected each indoor environmental comfort indicator as important. It does not show the amount of importance placed on each indicator.

*Elegance* is dependent of both EE related indicators (*Temperature* and *Noise*,  $p<0.01$ ) and live-long living indicators (*Flexibility*, *Intuitive controls*  $p<0.05$ , *Usability of spaces*  $p<0.01$ ). While *Adaptability* and *Flexibility* are dependent ( $p<0.01$ ), there is no statistically significant dependency between *Usability of spaces*, *Maintenance*, and *Accessibility*. EE-related indicators – *Temperature*, *Noise*, *Air quality* - are dependent to each other ( $p<0.01$ ).

Those who selected *Social activity* in the home as important also tended to select *Adaptability*, *Flexibility*, *Image & Identity*, *Privacy*, *View to outdoors* ( $p<0.05$ ) and *Natural light* ( $p<0.01$ ).

There is also a statistically significant dependency between *Age* and the importance of *Usability of spaces* in the home ( $p<0.01$ ). People younger than 40 were more likely to select *Usability* than those who were older. However, *Age* was independent of *Accessibility*.

### Triggers and goals

An increase in *Comfort* was selected by the largest number of people as a renovation trigger (70%) as well as renovation goal (68%) (see Fig. 2). Increasing *Energy Efficiency* is the second most important trigger and goal (54%). Other triggers range between 20% and 30% while other goals range between 18-42%. The difference between *Comfort* and *Energy Efficiency* is

statistically significant ( $p<0.05$ ), and so is the difference between *Energy Efficiency* and other triggers ( $p<0.01$ ) and other goals ( $p<0.05$ ).

There is very little change between triggers and goals with the exception of *Environmental sustainability* which is a trigger for 26% of respondents but becomes a goal for 42% of them ( $p<0.05$ ). While 68% of those who selected *Energy Efficiency* as a renovation trigger had *Environmental sustainability* as a goal, 100% of those who were triggered by desire for greater *Environmental Sustainability* had *EE* as a goal ( $p<0.05$ ).

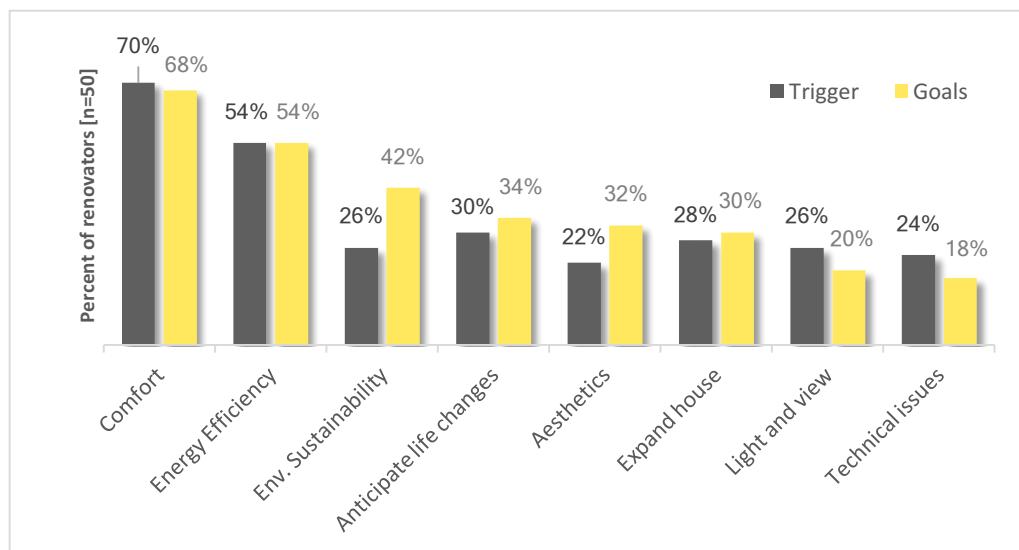


Figure 2. Triggers and goals of home renovations.

There is no statistically significant dependency between the use of an architect and changes from triggers to goals for *Comfort*, *Energy Efficiency*, *Anticipate life changes*, and *Environmental Sustainability*.

## Discussion

Several interesting findings can be gleaned from the results described above. About half of the 145 people choose between 7 and 12 factors that are of importance to them which demonstrates that IE Comfort is a multidimensional concept and that a home renovation (or new-built) needs to address several issues at once. All indicators were important to at least 30% of respondents while only 2% selected *Other*. Therefore the number of IE Comfort indicators presented to people can be considered concise and complete. The exception is *Artificial light* (12%), which suggests that this indicator can be left out in future studies.

*Natural light* stands out as the factor important to most people by far. Answering this demand for natural light has implications on many other indicators, such as *Temperature*, *Views*, *Privacy*, and *Accessibility*, where conflicts and synergies could be found. The next most important group of indicators are all LLL related while the EE indicators fall in the middle group. In other words spatial and design aspects are important more often than aspects that relate to energy use. This supports the idea that the appeal of energy efficient building or renovation by individual homeowners could be improved when packaged with (universal) design measures. The broader appeal of some LLL indicators, without being labelled as such, suggests that these measures could serve as a "foot in the door" for other energy and LLL measures, since it is easier to expand the scope of a project than to start one from scratch.

IE Comfort indicators are similarly important to people regardless of whether they plan to build new or renovate, or have no concrete plans yet. It shows that their decisions on what and how to renovate or build are determined by other factors.

*Comfort* as the most common trigger and goal of renovation confirms our hypothesis that comfort, as intuitively interpreted, is more appealing to people than energy efficiency or lifelong-living separately. This finding is in alignment with a pan-European research by Velux (2015) which found that 95% of Europeans assign comfort an above average importance, higher than energy costs, functionality or daylight. Since IE Comfort is effectively a more structured form of common use “comfort” derived by eliciting its meaning from residents in the context of home renovations it is reasonable to say that there is great overlap between the two terms. Therefore it can be argued that IE Comfort would be more appealing to people than either EE or LLL separately.

It was observed that very few people changed their positions between triggers and goals. Environmental sustainability was an exception here indicating that there is a desire to make the project environmentally sustainable once the decision to renovate has been made, often for other reasons.

Although it seems logical to hand responsibility for design related aspects to architects, the results suggest that architects are involved in less than half of renovations. Even when involved in renovations or as mandatory in new construction, no impact on renovation goals and importance of comfort indicators for people could be measured in this sample. Further research could explore the role, and willingness, of designers in promoting UD and EE measures.

Design elegance is a key tenet of LLL (Froyen, Dujardin, & Herssens, 2015; Mace, 1998) and it is correlated with both EE and other LLL indicators. It suggests that whatever functional measures are proposed, people prefer them to be elegantly done.

Surprisingly Age is not correlated with any factors other than *Usable spaces*. Younger people (under 40 years old) seem to place more importance on functionality, size and layout. This may be an indication that older people, who have usually lived in their homes for longer, are simply used to the usability of their homes and have no interest or ideas on improving them. We would expect older people to be more concerned about LLL aspects as accessibility, safety or ease of maintenance. However this was not the case.

## Conclusion

This paper explored the importance of indicators for comfort in the indoor environment in the context of homes built or renovated by homeowners. Here comfort is conceptualized as an integration of Energy Efficiency related aspects and aspects related to Universal Design.

The data support the idea that for homeowners comfort in the indoor environment is multifaceted and that our proposed list of indicators which includes both EE and UD related aspects can be considered concise and complete. It reveals that spatial and design indicators are important more often than energy efficiency related ones.

However, simply handing over the responsibility for more universally design and energy efficient homes to architects is not a solution due in part to their limited engagement in renovations. The development and decision making on the scope and important aspects of the project for the homeowner, consciously or not, happen very early in the process.

Comfort as renovation trigger and goal was shown to be more important than EE and LLL separately. This is an encouragement towards further employing IE Comfort as a user-focused concept for renovations which, while containing the same elements as EE and LLL, is

also appealing to lay-people – the homeowners who as clients of the renovation of their own home are in charge of the vision, scope and final decision making on the project.

## References

- Froyen, H., Dujardin, M., & Herssens, J. (2015). Designing for Sustainability: a Framework for Sustainable Architecture built on the Perspective of Universal Design.
- Kapedani, E., Herssens, J., & Verbeeck, G. (2016). *Energy Efficiency and Universal Design in Home Renovations – A Comparative Review*. Paper presented at the Universal Design 2016: Learning from the Past, Designing for the Future, York, UK. <http://ebooks-iospress.nl/volumearticle/44510>
- Kapedani, E., Herssens, J., & Verbeeck, G. (Accepted). *Comfort in the indoor environment: a theoretical framework linking energy efficiency and universal design*. Paper presented at the AHFE 2017 - 2nd International Conference on Design for Inclusion, Los Angeles, US.
- Mace, R. L. (1998). Universal design in housing. *Assistive Technology*, 10(1), 21-28.
- Van den Broeck, K. (2015). *Grote Woononderzoek 2013 - Deel 4. Woningkwaliteit en renovatie: resultaten op basis van de vragen aan bewoners*. Retrieved from Leuven:
- Velux. (2015). *Healthy Homes Barometer 2015*. Retrieved from [www.velux.com/healthyhomes](http://www.velux.com/healthyhomes)



# PLEA 2017 EDINBURGH

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## How to verify a Hybrid System Design for Adaptive Comfort with Dynamic Simulation Tools

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**Abstract:** This paper is about a Hybrid System Design that goes beyond conventional air-conditioning concepts in hot climates. In this approach, mechanical systems for air conditioning can be downsized substantially and energy demand can be reduced in the range of 30% to 50% without compromising thermal comfort and indoor air quality. This is not, however, a new concept. It is about a reconceptualization of the problem and understanding how to do more with less. The strikingly simple approach for Hybrid System Design can support a paradigm shift in building comfort design and help substantially reduce material and energy demand. The concept of Hybrid System Design combines excellent supply of tempered fresh air with fans that elevate air speed to satisfy thermal comfort requirements. The fresh air rates are designed for good indoor air quality and to keep carbon dioxide levels low. With rising indoor temperatures and higher humidity, the occupants can elevate the air speed at their location as per their personal preferences. This paper will describe the methodology of verification of hybrid system design with dynamic simulation tools with the example of an IT office design in Hyderabad, India.

**Keywords:** thermal comfort, adaptive comfort, hybrid system design, elevated air speed, energy efficiency

### Introduction

There is plenty of evidence that unlocking MEP design from very tight comfort envelopes is key to improving thermal comfort and reducing systems and energy demand. Many technical papers and reports highlight the energy saving potential of increased set point temperatures. Going beyond that and designing for higher indoor temperatures and humidity levels in combination with elevated air speed requires that designers be prepared for a discussion of all aspects of comfort and capable of verifying the proposed concept. We will address both aspects in the following sections.

The authors are aware that the terms Adaptive Comfort and Hybrid System Design need further clarification and might stretch their conventional meaning. In practice, within projects, this is partly intended to initiate a discussion with clients and design team to lay the groundwork for an informed discussion about re-thinking comfort. We use these terms in the absence of better ones.

### ***Hybrid System Design: high comfort – low tech – low energy***

The concept of Hybrid System Design combines excellent supply of tempered fresh air with fans that elevate air speed to satisfy thermal comfort requirements. The fresh air rates are designed for good indoor air quality (IAQ) and to keep carbon dioxide (generated by occupants) and other air pollutant levels low. With rising indoor temperatures, the occupants can elevate the air speed at their location as per their personal preferences. Typically, the air

speed can range from a low breeze (0.3 m/s) to a slightly noticeable airflow (1 m/s). As indoor air temperatures are allowed to rise, return air systems with heat recovery become less efficient and less relevant in tropical and subtropical climates with the ultimate consequence that mechanical systems can be simplified and reduced to supply air systems only. So even with highly efficient latent and sensible heat recovery systems the energy savings are low and easily outweighed by auxiliary energy demand for fan operation. At the same time, with only supply-air systems in place, there is a significant impact on investment cost.

### **The design process for Hybrid System design with Adaptive Comfort**

Common practice in many countries is to design air conditioned buildings that operate at 22 °C to 24 °C all year, satisfying the stringent specifications outlined in the established Thermal Comfort Standards of ASHRAE 55, ISO 7730, EN 15251 or other locally derived standards. In conventional HVAC design cooling loads are evaluated to guarantee that these maximum indoor air temperatures and humidity levels are never exceeded. This is simple and widespread, there are many computer design tools available which directly evaluate the internal and external cooling loads and proposed system design. Many of them perform a cooling load evaluation for a single maximum design point. The complex question of thermal comfort is reduced to a temperature and humidity set point. When designing for adaptive comfort, six environmental and personal parameters, air temperature ( $T_{air}$ ), mean radiant temperature (MRT), relative humidity (RH), average elevated air speed ( $v$ ), clothing factor (clo) and metabolic rate (met), are considered. This requires that the building design be evaluated with dynamic simulation tools and adaptive models be applied to verify comfort. The design focus is shifted from air temperatures (or operative temperatures) to a more comprehensive comfort parameter: Predicted Mean Vote for elevated air speed (PMVeas). The greater set of parameters introduces greater complexity, but offers more opportunities to create comfortable conditions.

#### ***Modelling the Predicted Mean Vote for elevated air speed (PMVeas) according ASHRAE 55-2013***

Models for the Predicted Mean Vote have been introduced in many simulation software packages as PMV models. It is important to understand that this classical PMV model by O. Fanger differs substantially from the PMVeas model particularly regarding the sensitivity to breezes or, technically speaking, to elevated air speed.

Underpinned by a heat balance model developed in the 1970s for air conditioned spaces, the derived 'static' comfort standards tend to prefer lower temperatures and low air speeds as achieved with conventional air-conditioning techniques. Being developed in mid-latitude climates, systematic discrepancies were found when applied to warmer climates. The heat balance comfort model does not fully explain thermal comfort conditions experienced in naturally ventilated buildings with elevated air speed (de Dear, 2011).

Adaptive comfort models, developed based on extensive field studies across the world, can describe this phenomenon (Humphreys et al. 2016). With ASHRAE Standard 55-2013, Appendix G, Addendum d, a procedure for evaluating the cooling effect of elevated air speed is described. One tool including PMVeas for a static condition is the CBE Thermal Comfort Tool developed at the University of California Berkeley (Hoyt, 2013). For dynamic thermal simulation this procedure has been incorporated into TRNSYS 3D since the release of version 17.

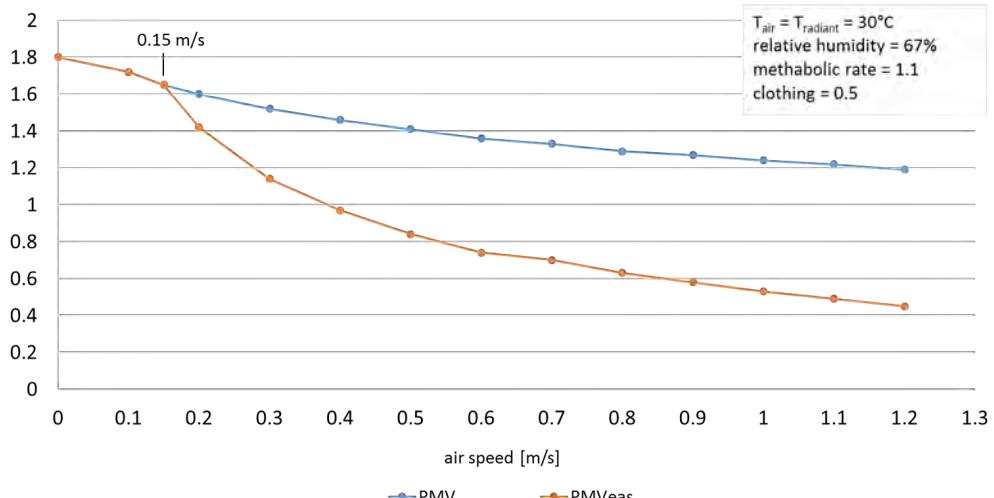


Figure 1. Comparison of sensitivity of PMV and PMVeas to air speed. The PMV is not very sensitive to elevated air speed. For Adaptive Comfort design the PMVeas model (ASHRAE 55-2013, Appendix G, Addendum D) should be used. Example: for 1.2 m/s, an operative room temperature of 30 °C is perceived as neutral with a PMVeas < 0.5. With the conventional PMV of 1.2 the conditions would be falsely rated as slightly warm – even with the breeze.

**Three main characteristic steps can be identified for the Hybrid System design process:**

1. **Introducing the PMVeas as design objective** for thermal comfort
2. **Cooling load evaluation and design optimization with dynamic simulation** to achieve maximum room air or operative temperatures of 28 °C and a relative humidity < 70%. This step yields 3 of the required design parameters which describe the building quality, IAQ and system performance: Tair, MRT and RH.
3. **Comfort evaluation** with the adaptive comfort model with auto-clothing and auto-elevated air speed strategies to verify that design objectives, e.g. PMVeas < 0.5, are achieved. This can form part of the dynamic analysis or be evaluated in a post process. In this step, the two personal parameters, clo and met, are considered, the **design is verified and the optimal air speed v is evaluated** (6<sup>th</sup> parameter).

#### **Step 1: Introducing PMVeas as a design objective to the design process**

One of the most important steps in the design process with the client and design team is to introduce the PMVeas as the design parameter for thermal comfort and to replace the simple maximum temperature set point. ASHRAE compliance is achieved when -0.5 < PMVeas < 0.5, which is equivalent to 90% of the occupants being satisfied with the environmental conditions and is the best result which can be achieved in practice.

#### **Step 2: Cooling load evaluation and design optimization with dynamic simulation tools**

With dynamic simulation tools the thermal performance of a design can be reliably evaluated while accounting for the local climate, program, internal loads and operation. Effects of passive envelope qualities such as thermal insulation, solar protection, solar gain, thermal mass, infiltration, materials, colours and many more can be studied in combination with active systems for HVAC. The authors want to emphasise that all options to reduce external and internal loads shall have preference, but that is not the topic of this paper.

## Hybrid System design

The concept of Hybrid System Design is to create an excellent fresh air supply and to maximize the cooling effect of the tempered supply air. The fresh air rates typically range from 18 cfm ( $30 \text{ m}^3/\text{h}$ ) up to 27 cfm ( $45 \text{ m}^3/\text{h}$ ). Supply air is typically tempered to  $20^\circ\text{C}$  and dew point with no further dehumidification. To further optimize comfort and cooling energy, active cooling strategies such as variable air volume (VAV) systems, reduced supply air temperature set points (e.g.  $18^\circ\text{C}$ ), energy efficient technologies (e.g. sensible and latent heat recovery), radiant cooling (floor and ceiling) are studied in combination with natural ventilation. By limiting cooling capacities and mass flows in the simulation, the hours when set points are exceeded can be studied.

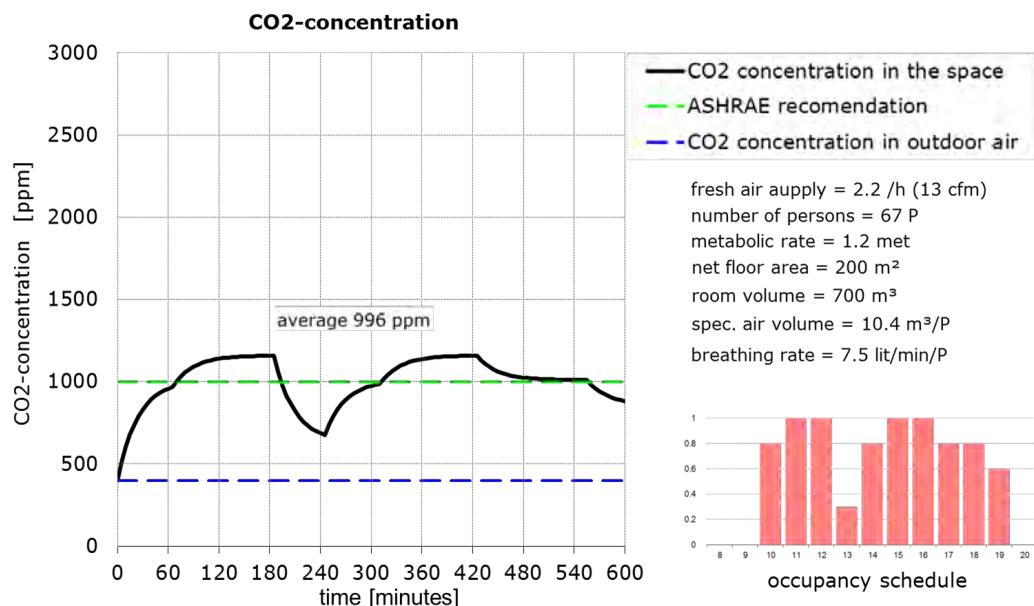


Figure 2. Study of indoor CO<sub>2</sub> level over the course of the day. Example is for 13 cfm.

The different design alternatives are also compared with respect to electrical energy demand, particularly auxiliary energy demand for mechanical ventilation. As indoor air temperatures increase it is found that cooling energy savings from heat recovery are outweighed by the additional auxiliary electrical energy demand. Thus, it was found that the return air system could be omitted and the exhaust air could be spilled over to adjacent semi-enclosed areas. Mechanical systems could be simplified, investment costs and space requirements for ducts and mechanical systems could be reduced without compromising the performance, energy demand and comfort (Kessling et al. 2014 and 2016). This step typically yields 3 of the required design parameters which describe the building quality system performance Tair, MRT and RH.

### Step 3: Comfort evaluation and design verification

#### Auto-clothing

People are able to adapt their clothing to the prevailing climatic conditions. To consider this aspect, we propose a typical range for clothing factor depending on the local climate, the local cultural preferences and the intended use of the building. ASHRAE e.g. suggest a clothing factor for 0.5 for summer and 1 for winter. To simplify the modelling, we suggest defining the clothing factor based on the ambient conditions: e.g. assuming that people wear typical

summer clothing when  $T_{air} > 21^{\circ}\text{C}$ . This decision will yield the clothing parameter for every time step of the dynamic simulation. Together with the anticipated occupation the metabolic rate is set and both personal parameters are defined.

### **Auto-elevated air speed (Auto eas)**

In a last step, with the 5 previously identified parameters the PMVeas is evaluated for different air speeds and the optimal air speed is chosen by an algorithm. In practice 4 thresholds are typically employed:

1.  $v_1 = 0 \text{ m/s}$  (no air movement at all),
2.  $v_2 = 0.3 \text{ m/s}$  (air movement hard to notice, but beneficial for comfort),
3.  $v_3 = 0.8 \text{ m/s}$  (maximum allowed air movement when people cannot control air speed according to ASHRAE 55),
4.  $v_4 = 1.2 \text{ m/s}$  (maximum allowed air movement when people can control air speed according to ASHRAE 55).

This modelling reflects the adaptive choices of people in an office or design studio equipped with fans whose individual speeds can be controlled by the users. For more conservative design evaluations, the maximum air speed can be limited to 0.7 m/s.

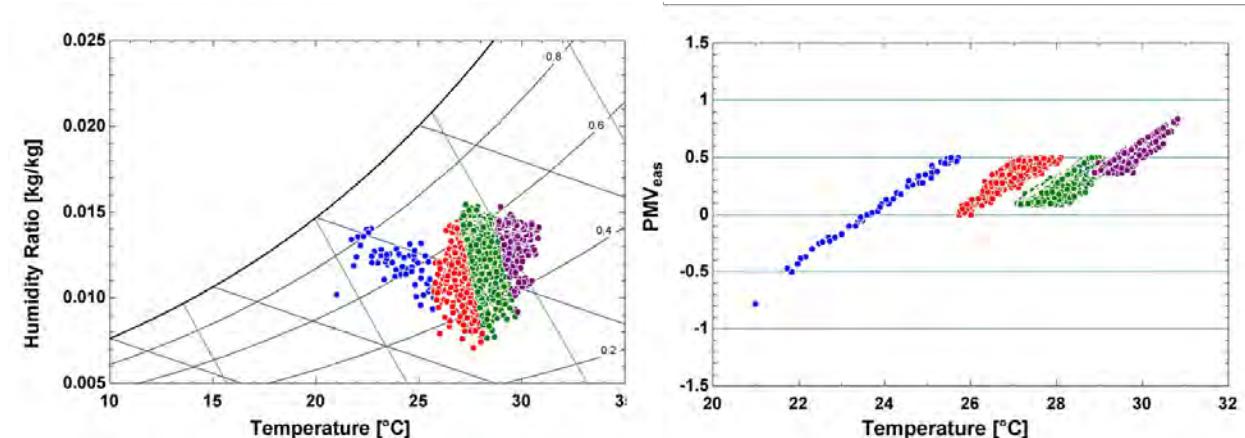


Figure 3. With the Auto eas algorithm the optimal air speed is identified. The result shown are for an IT office with Hybrid System Design. Left: conditions in a psychometric chart. Right: the comfort conditions rated with PMVeas. The colors indicate the different air speeds in m/s: blue: 0, red 0.3, green 0.7, purple: 1. The graph shows how the elevated air speed compensates for higher indoor temperatures. This control algorithm mimics people adaptive choices to control their thermal environment with a ceiling fan.

### **Example of Hybrid System design for an IT office, Hyderabad**

The Hybrid System design is highlighted in the design of an office for a large IT campus in Hyderabad India and compared to a typical AC design. The density is high with 67 working desks in 200 m<sup>2</sup>. The total internal loads, including computer, screens and people, are 50 W/m<sup>2</sup>, a high value.

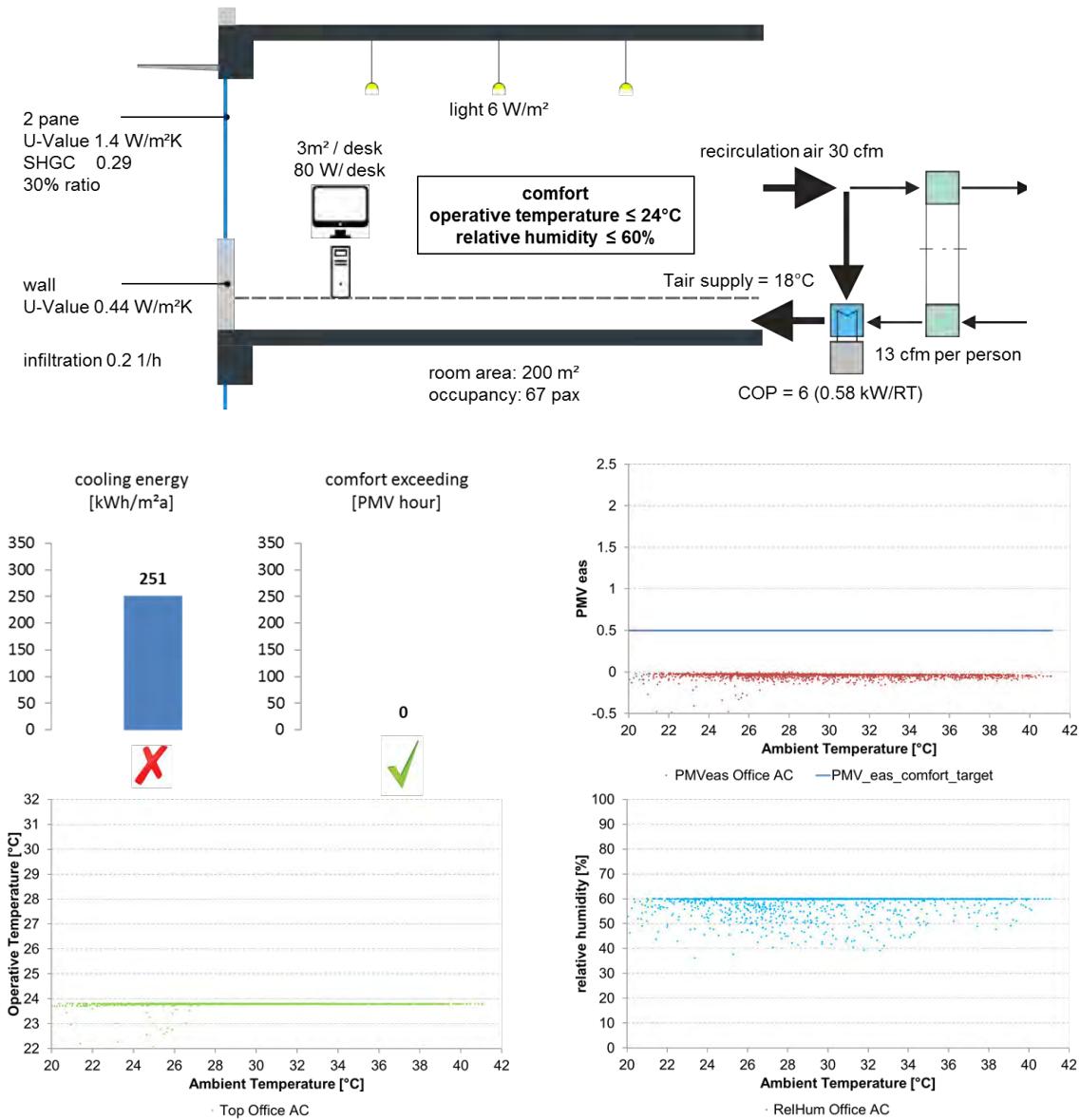


Figure 4. Full A/C with heat recovery. Schematic of passive and active systems and evaluation of energy and comfort.

Even though options to reduce internal electrical loads such as energy efficient laptops, screens or thin client solutions have been discussed with the client they are not discussed here to showcase that Hybrid System design is suitable for spaces with high internal loads. From the many studied options to compensate the high internal loads (return air systems, radiant cooling and combination thereof) only two return air options, both with a supply air temperature of 18 °C, are shown. In both options the fresh air is supplied at a rate of 13 cfm. This represents a compromise between higher fresh air rates proposed by the design team and the lower standards of the client.

The schematics for both options show the passive qualities of the envelope and the boundary conditions for the operation of active systems. The diagrams show the results for operative temperature, relative humidity and PMVeas as well as cooling energy and hours when comfort is exceeded (anti-clockwise from bottom left).

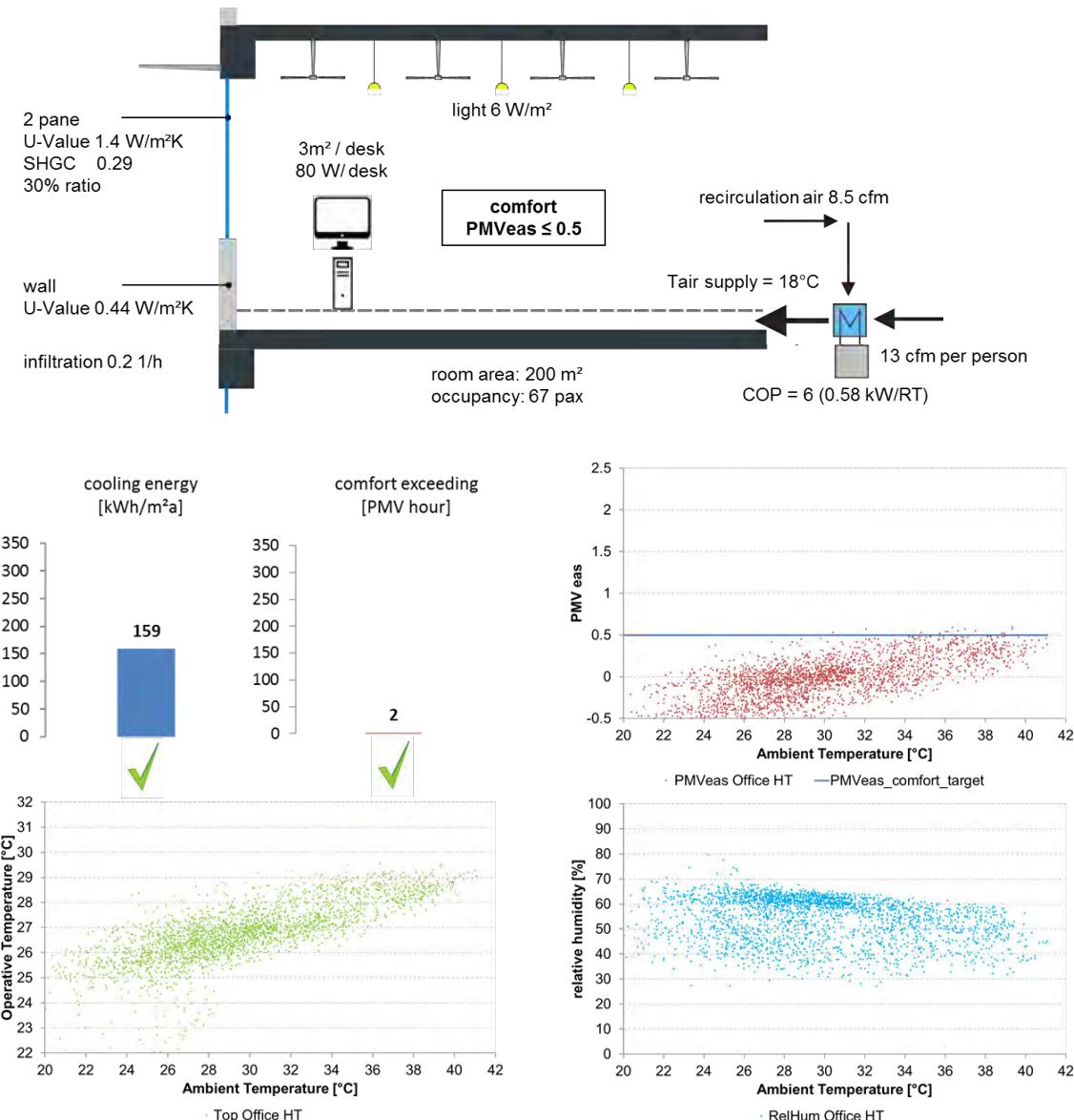


Figure 5. Hybrid System design. Schematic of passive and active systems and evaluation of energy and comfort.

In Figure 6 technical features, energy and comfort of the two options are compared to inform the client's decision.

For the full A/C system (Figure 4) indoor room temperatures are set to 24 °C and relative humidity is set to < 60%. The system provides excellent comfort, but requires significant energy use.

With the Hybrid System approach (Figure 5) the air temperatures range up to a maximum of 29 °C. The air speed is limited to a maximum of 0.7 m/s. The return air system flow can be reduced by about 70%, thus the floor height of the raised floor can be reduced and the clear room height increased by 20 cm. Comfort is good with a PMVeas of < 0.5, while the total electrical energy demand is reduced by 35%. The reduced return air system without heat recovery also offers substantial cost savings.

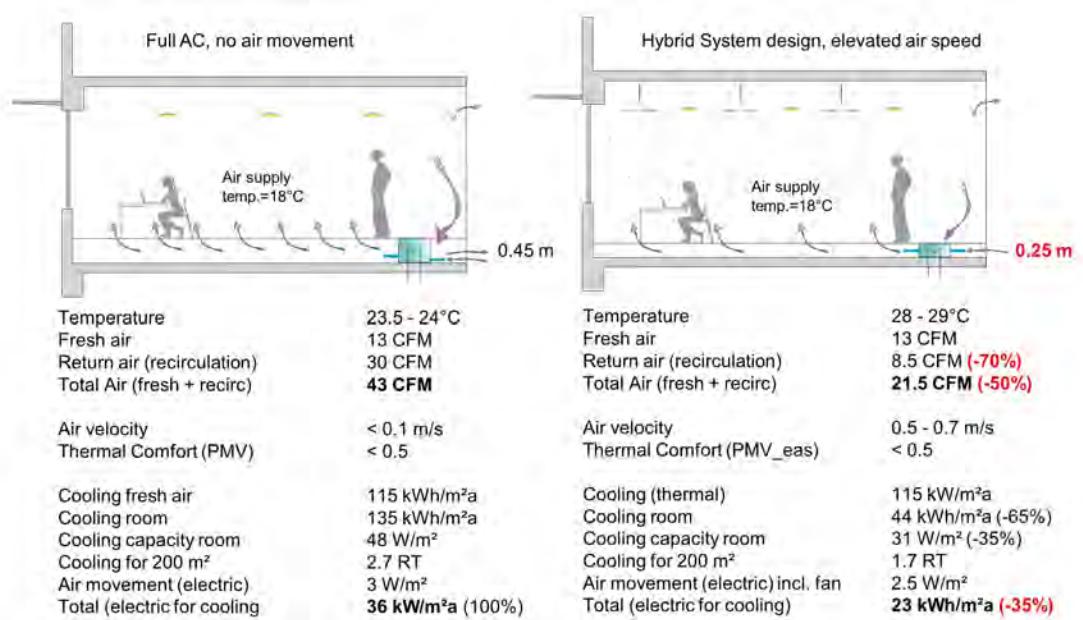


Figure 6. Comparison of systems, features, energy and comfort.

## Conclusion

For comfort design a holistic view of all the parameters which make up human comfort is key. Designers can broaden design strategies from focusing on a single temperature set point to include physical phenomena of heat radiation as well as environmental parameters such as wind speed to design for adaptive environments. In warm climates, a Hybrid System Design presents an attractive choice to create comfortable environments with smaller air conditioning systems, reduced chiller capacities and lower energy demand. Adaptive Comfort and Hybrid Comfort Design is not a poor man's choice. It is a choice for new, breathing architecture, for new aesthetic and functional solutions, for opening up façades with better indoors-outdoors connections, and for context sensitive design in response to local climate and cultural conditions.

## References

- ASHRAE Standard 55 (2013). *Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE.
- EN 15251 (2012). *Indoor Environmental input parameters for design and assessment of energy performance of buildings*. European Norm.
- ISO 7730 (2012). *Ergonomics of the thermal environment*. International Organization for Standardization.
- de Dear, R. (2011). *Adaptive Thermal Comfort, Background, Simulations, Future Directions*, <http://eetd.lbl.gov/sites/all/files/dedear-sem04feb2011.pdf>.
- Humphreys, M. Nicol, F. Roaf, S. (2016). *Adaptive Thermal Comfort - Foundation and Analysis*. ISBN: 978-0-415-69161-1, London: Routledge.
- Hoyt, T. et al. (2013). *CBE Thermal Comfort Tool*, Center for the Built Environment, University of California Berkeley. <http://cbe.berkeley.edu/comforttool/>.
- Franke, L. Kessling, W. Engelhardt, M. Wong, M.S. (2014) *Evaluation of Comfort Concepts with Tempered Air and Elevated Air Speed in Tropical Climates*. PLEA Conference, Ahmedabad, India.
- Kessling, W. Engelhardt, M. Kishnani, N. (2016) *Developing the Net Zero Energy Design for the School of Design and Environment of the National University of Singapore*. PLEA Conference, Los Angeles, USA.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Strategies to Improve the Thermal and Visual Comfort of the Informal Settlements in India

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**Abstract:** One third of the world's total population is from the urban areas of the middle income nations. The cities are growing and so is the need to provide basic shelter. The lack of provision of affordable homes in the urban areas leads to encroachment and unplanned development. One such city where more than 50% of its population lives in such settlements is Mumbai, India. The thermal and visual comfort in these spaces are achieved by using air-conditioning and artificial lighting, which increases their energy consumption and household expenditure. Thus, the main focus of the investigation was to study the existing living conditions and to find retrofitting strategies in order to improve their living environments and offer the inhabitants passive alternatives to the increasingly widespread use of mechanical options. The study suggested incorporation of strategies like fenestration design to achieve variable ventilation rates, to reduce the risks of overheating as well as the allowance of required amount of daylight whilst simultaneously minimizing the solar gains. The fieldwork and computational analysis aided in concluding that, these developments had high scope for improvement, hence adopting careful strategies would considerably improve the habitable conditions of its user along with sustaining its socio-cultural importance.

**Keywords:** Informal settlements, Adaptive strategies, Comfort, Socio-cultural factors.

### Introduction

At present, every developing nation is facing an acute shortage of shelter for its citizens followed with partial distribution of food and livelihood. With the growing population, these nations are also the worst affected areas that experience severe life and goods damage during natural calamities. High density, minimal housing, affordability, poor sanitation were some of the reasons for maximum loss during one such catastrophe that Mumbai experienced during the July 2005 floods. Therefore, it becomes extremely important to look at the existing living environments, understand them, learn from them and apply the learnings in order to minimize the damage and improve the living standards. At the same time, it is also important to make space for a progressive and sustained socio-economic development over the long term.

The emergence of mega-cities during the late 20<sup>th</sup> and early 21<sup>st</sup> century also brought with it, global economic transformations and fundamental changes in terms of national growth and development strategies. During this time and even today, Mumbai, is undergoing massive construction that includes high-end office towers, malls and luxury housing projects. However, simultaneously the city has also been experiencing an explosion of unplanned settlements that include small home based workshops, street vending and informal housing. These settlements are often looked upon as areas that are on the verge of

collapse and the ones that possess a threat to the health and safety of the city. The fact that these settlements are remarkably rich in cultural, spatial and social qualities is often ignored (Raith, 2012). One such example of an informal settlement is Dharavi, Mumbai. Known as the largest slum in Asia, Dharavi has a lot to teach and holds qualities for further improvisation in the living and working environments of its inhabitants and setting an example to be replicated (Fernando, 2009).

### **Design Research Objectives**

In order to solve the issue of the informal settlements, the SRA – Slum Rehabilitation Act was setup in Mumbai in 1996. Under the SRA, the developers were meant to provide free housing to the occupants of the informal settlements, in return they were granted density bonuses, which gave them the freedom to build above the density limit (Gregory, 2010). Thus, when one looks at the housing provided by the SRA, one cannot neglect the poor quality and question the sustainability of these developments. Clearly, the Slum Redevelopment program is not in favour of its inhabitants, since the scheme is focused only in providing poor quality apartments with zero work spaces. Hence, to improve the living conditions of the people, there was a need to identify the spatial and environmental qualities and shortfalls of the current informal development. In order to study the existing up growth the following questions were explored:

- What lessons could one learn from the unplanned development?
- Was there a need for rehabilitation?
- Why these developments were termed sustainable?
- What were the comfort criteria's of the inhabitants of the informal settlement?
- Was it possible to achieve thermal and visual comfort in such dense urban setting?

There was a need to rethink the rehabilitation program and provide improved solutions that understood the existing urban fabric of these settlements and accordingly build its strategies focusing on its inhabitants, then the city and then for the profits of the developers.

### **Context**

#### **Climate**



Figure 1. Yearly Average Conditions of Mumbai (Derived from Meteonorm 7)

Although the average annual temperature in Mumbai ( $19.0760^{\circ}$  N,  $72.8777^{\circ}$  E) remains in the range of  $25^{\circ}\text{C}$  to  $30^{\circ}\text{C}$  throughout the year, the climate of Mumbai can be described as hot and humid, with three main seasons of summer, monsoon & winter. During the months of winter, the minimum average temperature reaches  $24^{\circ}\text{C}$  while during summer the maximum average temperature obtained is about  $30^{\circ}\text{C}$ . It is evident that during the months

of monsoon the humidity level reaches as high as 80% during which a drop in temperature (average temperature during this time is about 26°C to 27°C) and comparatively higher wind velocity (maximum 4.5m/s) is also observed. With the cloud cover during monsoons, the solar radiation received also drops considerably (Figure 1.). High temperature (maximum 34°C) and solar radiation levels (6.5 kWh/m<sup>2</sup> - mean maximum in April) throughout the year signifies that ventilation rate, window aperture and efficient shading devices would play an important role for the building to observe passive cooling strategies.

### **Field Investigation**

With a density of about 350,000 to 600,000 inhabitants/km<sup>2</sup>, Dharavi is a home to about 80 different communities. In spite of the vast cultural diversity, it is a peaceful neighbourhood and is not just a place to live but also for production (Savchuk and Encanove, 2008).

### **Methodology**

As per the literature study, this extremely efficient and dense development with narrow lanes and cantilevered upper floors, blocked the sunlight and produced a comparatively cooler microclimate (Dovey and Tomlinson, 2012). Hence, it was important to test this parameter to prove the significance of the spatial characters of these informal clusters. A fieldwork study helped in observing and mapping the existing living and working spaces and the comfort conditions of the inhabitants of the informal settlements. A pre-design analysis study generated proposals for alternate design schemes to address the issues and help the community. The strategies were further tested through various computational simulations to determine the best suitable adaptive strategies that could be adopted to achieve maximum indoor comfort at an affordable rate.



Figure 2. Existing Built Fabric – Dharavi (Outdoor alleyway, Existing Layout and Indoor Space)

### **Existing Thermal and Visual Condition: Spot Measurements & Continuous Measurements**

Sector 5 of Dharavi was chosen for fieldwork, which roughly represented the overall working and housing stock of Dharavi. A 30m<sup>2</sup> ground floor household (Owner: Paul Raphel) was chosen for indoor environmental analysis and the spot measurements were quantified for the household and the area around it, to understand the microclimate the built environment created and how it affected the indoor climatic conditions. The data collected from the fieldwork was subsequently analysed and pre-design strategies were tested based on the fieldwork analysis.

**Outdoor:** The spot measurements taken in the outdoor spaces and alleyways verified that the shaded alleyways aided in maintaining lower temperatures by blocking the solar radiation. However, this obstruction also led in cutting off the daylight entering the

alleyways, making them dark during the day. This in turn led to zero daylight in the living spaces. The main reason for the shaded alleyways was the incremental growth of the settlements which was directly proportional to the economic growth of a family (Figure 2).

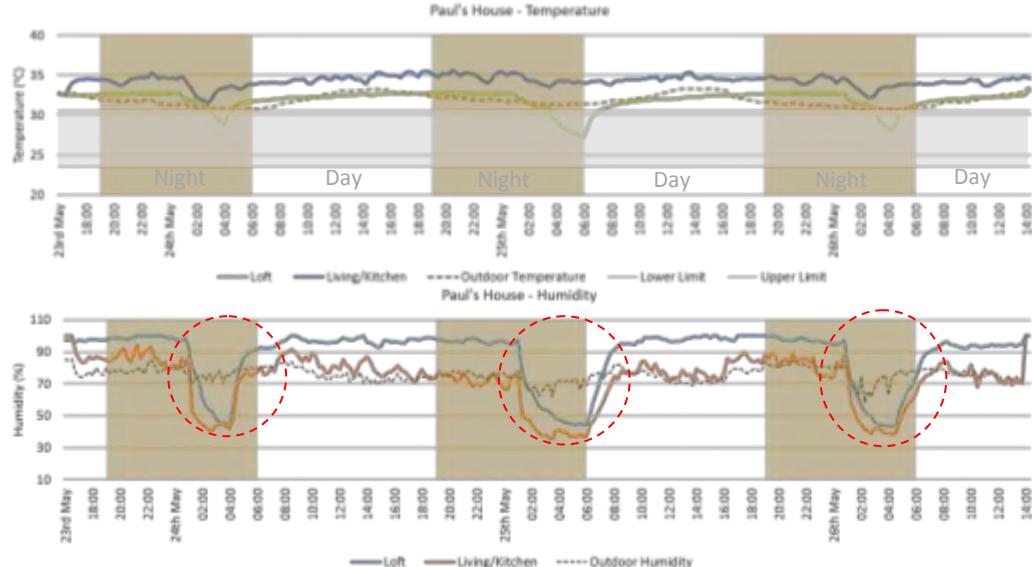


Figure 3. Fieldwork - Continuous Measurement –Temperature & Humidity

**Indoor:** The values obtained from the data loggers were plotted along with the comfort band and it was observed that the indoor temperature (maximum – 32 to 35°C) and humidity levels (maximum – 90 to 95%) were higher than the outdoor temperature (Figure 3). Indoor drying of clothes, higher occupancy levels, lower air changes per hour were some of the factors that contributed to higher humidity levels in the house. The drop in the humidity and temperature was due to the use of air conditioning unit, since the unit not only cooled the air but removed moisture as well (Figure 3). Thus, in order to obtain thermal comfort indoors, ventilation became one of the major concerns for this typology.

## Design Application

### Strategies

The fieldwork aided in concluding that though Dharavi was one of the most sustainable developments, the thermal and visual quality that was experienced (indoor and outdoor) during the fieldwork could not be neglected. Hence, a step by step process to understand the user requirements and the possible ways in which minimum comfort requirements could be met, were taken into consideration. The possibilities of development that were established in order to evaluate the proposal were as follows:

- Alterations – This consisted of - i. Change in roof; ii. Change in window to floor ratio; iii. Change in the drainage system; iv. Change in the wall system
- New Development – This consisted of - i. A new design development keeping the existing footprint; ii. Application of learnings from the ‘Alterations’ to the new development.
- Completely New Development – i. This would mean a completely new design, with new density ratios and open spaces; ii. A complete change in the design and culture of the existing fabric. Considering the first possibility of development, the following design interventions were proposed and analysed:

### The Cases:

#### Existing Case (Figure 4.):

With no windows, two doors that opened in the alleys on either side of the room, were partially kept open for the purpose of ventilation when required and was the only source of light.

#### Case A (Hybrid Downdraught Cooling) (Figure 5.):

One window (size: 1.7\*0.35m) that opened in the social alley (orange) and the other window (size: 1.7\*0.35m) that opened in the drainage alley (blue), were proposed after calibrating their sizes and stack heights (0.9m) in Optivent 2.0 in order to achieve the required ventilation rate. In this case, the drainage alley (blue) was proposed as a cooling tower. Cooling coils were positioned on top, so that fresh air would be cooled using the coils which would then be distributed in individual houses. It was then estimated that, hot air from the houses would exhaust into the social alley. Thus, maintaining a continuous air flow.

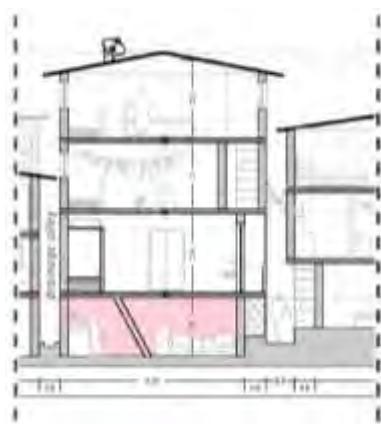


Figure 4. Existing Case

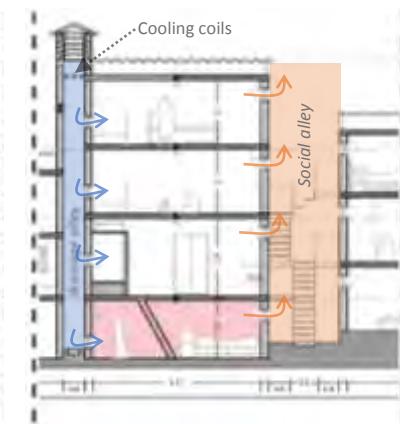


Figure 5. Case A

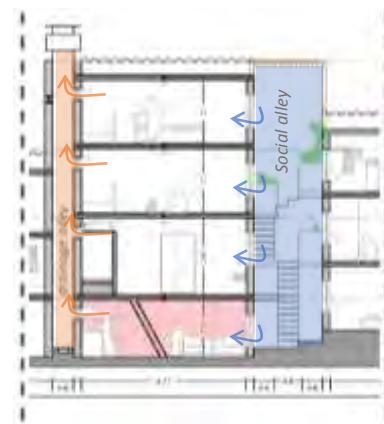


Figure 6. Case B

#### Case B (Stack Ventilation) (Figure 6.):

One window (openable window size: 1.7\*0.35m & fixed window size: 1.7\*0.65m) that opened in the social alley (blue) and the other window (size: 1.7\*0.35m) that opened in the drainage alley (orange), were proposed after calibration. The social alley (blue) in this case was shaded with pergola on top and planters all along the alley, to achieve cooler temperature. This cooler air was then distributed in the houses. It was then anticipated that the hot air from the houses would then get exhausted in the drainage alley (orange).

### Analytic Work

#### Ventilation Strategy

Window proportions played an important role because they determined the amount of daylight levels in the house and also directed the air flow movement. Thus, various permutations and combinations for the inlet size, stack height and the aperture size for the window were calibrated in Optivent in order to determine the best suited option that could be adopted for the given typology. It was observed that, when the window size was maximized, highest air changes per hour was achieved. However, with the dense format of the existing development it was not practical to suggest openings of 2m\*1m. Hence, the second best option was chosen, where though the window size was smaller (1.7m\*0.35m), higher air changes per hour was achieved by considering maximum stack height of 0.9m.

## **Daylight Strategy**

Daylight study was performed for the two seasons of summer and winter. However for the purpose of this paper, only summer scenario for both the cases is explained in detail.

### **Case A (Figure 7):**

Ground Level - It was observed that the amount of daylight received on the ground floor level during a typical sunny day with an outdoor illuminance of 15500lux, was approximately 90-150 lux in half the house while the remaining half received less or minimum daylight during the morning hours. The daylight level gradually increased, with 150-270 lux during noon, whereas post-noon the illuminance level achieved was 50-300+ lux throughout the house. Top Level (4<sup>th</sup> floor) - The amount of day light received during a typical sunny day was around 100-300+ lux throughout the day.

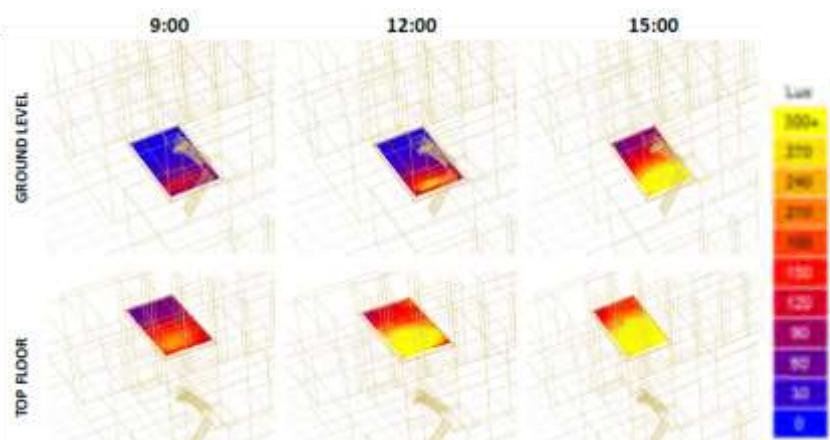


Figure 7. Daylight Analysis – For Summer (May) - Case A (Derived from Ecotect)

### **Case B (Figure 8):**

Ground Level - In spite of the shaded alleyway, the daylight level achieved was much higher as compared to Case A. The fixed windows aided in achieving indoor visual comfort. Top Level (4<sup>th</sup> floor) - The daylight level achieved was 300+ lux throughout the day. Which meant the fixed window made the indoor visual environment, uncomfortable.

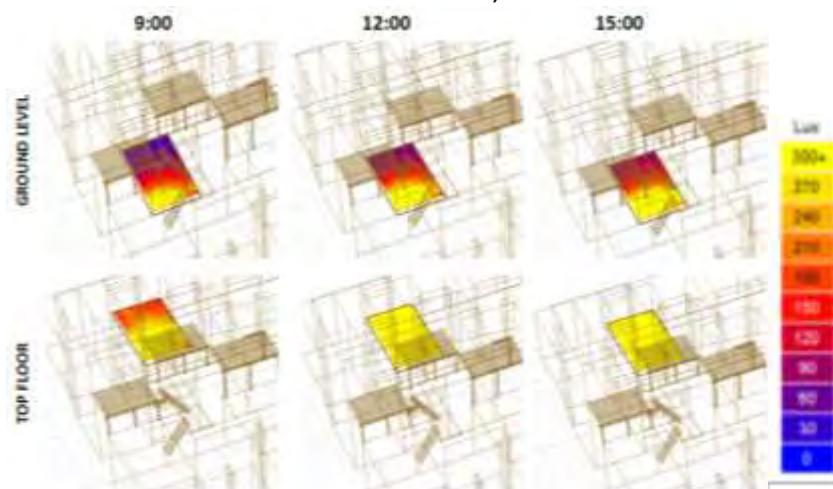


Figure 8. Daylight Analysis – For Summer (May) - Case B (Derived from Ecotect)

Hence, it was concluded that providing a fixed glass window (Case B) along with openable slit window on ground level could improve the daylighting conditions of the house during most times of the year. The daylight levels achieved on the top level in Case A was not up to the standard requirement, while the levels achieved in Case B were way higher

than the standard requirement, which meant higher solar gains. Hence, the analysis developed two possibilities that could be applied: 1. To provide lower level with openable as well as fixed window to achieve maximum daylight and provide top level with an openable slit window only, so that it does not exceed the daylighting requirement. 2. To provide all the levels with fixed window along with openable window and provide adaptive strategies such as curtains for the users to adjust the daylight levels in the house as per their needs.

### Thermal Analysis

The lack of ventilation caused higher indoor temperatures along with increase in the humidity levels and hence cross ventilation was needed. The occupancy gains, equipment gains and occupancy patterns were calculated in order to perform TAS Simulations. A thermal comfort band from ASHRAE 55 model (CBE thermal comfort tool), with 80% acceptability limit was considered for the thermal analysis.

#### **Typical Summer Days**

On Global Radiation: According to the climate data obtained from Meteonorm and TAS Simulations, maximum radiation ( $1000\text{Wh/m}^2$ ) was received from 11:00-13:00, for the analysed days, from 24<sup>th</sup> May to 27<sup>th</sup> May (Figure 9). Gradual rise and fall in external temperature from 6:00-19:00 could be associated with the global radiations. The temperature dropped by a maximum of  $7^\circ\text{C}$  when there were no radiations i.e. during night.

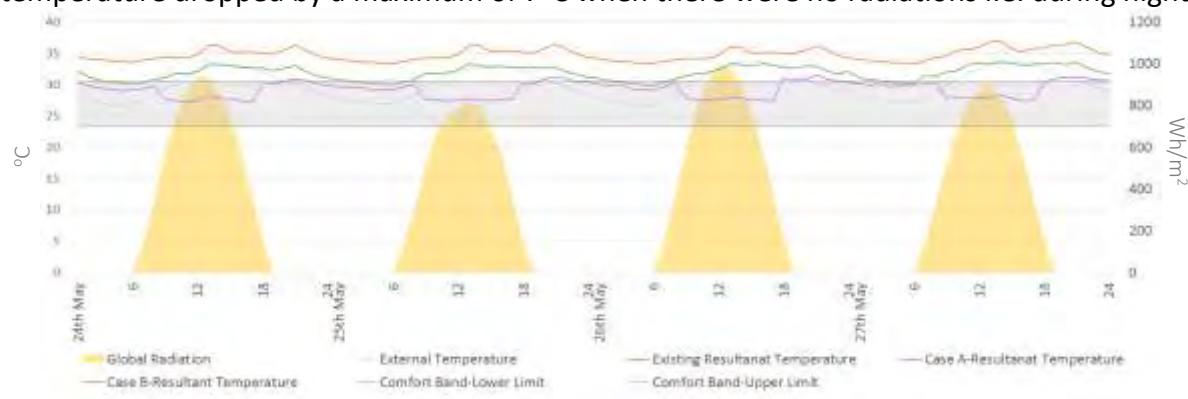


Figure 9. Typical Summer Days – 24<sup>th</sup> May to 27<sup>th</sup> May – Ground Level (Derived from TAS)

Existing - Apart from global radiation, internal heat gains and lack of ventilation were the key reasons for higher indoor resultant temperature in the existing scenario. Case A - The cooling coils were set to operate from 9:00 to 17:00 when the global radiations was higher. Hence, consistent drop in temperature was observed during this period. Case B - With no mechanical cooling, 5-6°C drop in the resultant temperature as compared to the existing case was observed.

Thus, it was observed that, the cooling coils worked satisfactorily and managed to maintain the indoor resultant temperature within the comfort band throughout. But, with no mechanical ventilation, Case B also worked exceptionally well and managed to get the temperatures in the comfort band.

### Conclusion

The fieldwork and the computational analysis aided in concluding that effective ventilation strategies with appropriate stack heights, worked in favour of the hot and humid climate.

Case A (Hybrid Downdraught Cooling) – In spite of the climatic conditions, this method reduced the internal resultant temperature by  $8^\circ\text{C}$ . However, since the cooling coils

tend to increase the moisture content in the atmosphere, they also increase the overall humidity levels. Moreover, since the cooling coil unit was shared by approximately three households, it was more affordable and efficient as compared to the present norm of having individual air conditioning units. Although the daylight levels achieved in this case on the top level was as per the standard requirement (within 150-300 lux), the lower level however received comparatively lower daylight levels (within 0 – 120 lux).

Case B (Stack Ventilation) - This option was purely based on natural ventilation and on the buoyancy effect. A considerable drop in temperature (5-6°C drop) was observed with this option as well and the obtained results projected that the temperatures were within the comfort band without any mechanical ventilation. Case B was more effective in terms of daylight levels, leading to considerable amount of reduction in the use of artificial light in the living spaces. The daylight levels received were on the higher side with this option (300+ lux) on the higher levels and thus adaptive design strategies were suggested in order to achieve required visual comfort.

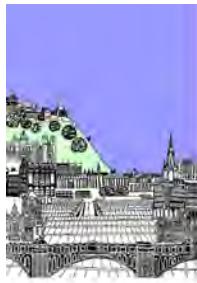
Therefore, by incorporating small adaptive strategies, the social and cultural importance of these settlements could be retained and the thermal and visual comfort of the existing spaces could be considerably improved as well. There are numerous ways in which the living conditions of the informal settlements can be upgraded and all the calibrations and analysis proved that there are high chances that these ways were practical and achievable. Thus, the government does need to rethink the Slum Rehabilitation Act, since these slums have a great potential in becoming the most sustainable self-made developments and at the same time have the ability to retain its social and cultural fabric.

## Acknowledgements

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## References

- Cronin, A.A. (2004). *Water and Sanitation in the World's Cities: Local Action for Global Goals*. UK and USA: Earthscan Publications Ltd.
- Dovey, K. and Tomlinson, R. (2012). *Dharavi: Informal Settlements and Slum Upgrading*. Melbourne. University of Melbourne. Available from <http://www.placeresearch.net/pdf/DHARAVI%20report.pdf>. [Accessed 29 April 2015].
- Fernando, V. (2009). *In the Heart of Bombay: the Dharavi Slum*. Available from <http://base.d-p-h.info/fr/fiches/dph/fiche-dph-7867.htm#Haut>. [Accessed 27 April 2015].
- Ford, B., Schiano-Phan, R. and Francis, E. (2010). *The Architecture & Engineering of Downdraught Cooling: A Design Sourcebook*. U.K. PHDC Press.
- Grima, J. and Gandolfi, N.M., 2012. URBZ Urbanistica collettiva. *Domus*, (955), pp.54.
- Gregory, R. (2010). Urbanism. *Architectural Review*. September. (228), pp.88-91.
- Gupta, V., 1981. Natural cooling of buildings. *RR-SI, Innovative Informations Inc., Greenbelt, MD*.
- Gupta, V., 1984. Indigenous architecture and natural cooling. *Energy and Habitat*, pp.41-58.
- Raith, K. (2012). Dharavi, Mumbai – The value of a Slum. *Architektur Aktuell*, (391), pp.72-85.
- Savchuk,K. and Encanove,M. (2008). *Urban Typhoon Workshop in Koliwada, Mumbai*. Available from <http://www.urbantyphoon.com/dharavi.htm>. [Accessed 27 April 2015].
- Tregenza,P, Wilson, M. (2011). *Daylighting: Architecture and Lighting Design*. Routledge.
- Tyler,H. et al. (2013). ASHRAE-55. *CBE Thermal Comfort Tool*. Available from <http://cbe.berkeley.edu/comforttool/>. [Accessed 25 June 2015].



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*Design to Thrive*

## Evaluating Thermal Environment and Thermal Comfort in Schools Located in Kashan-Iran in Mid-Seasons

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**Abstract:** The study seeks the impact of design on thermal environment of a high school with courtyard design and of a primary school with compact design in mid-seasons in Kashan, hot and dry part of Iran, and studies students' Thermal Sensation Votes (TSV) and investigates their compatibility with Predicted Mean Vote (PMV) suggested by ASHRAE Standard 55. Indoor environmental parameters including air temperature, relative humidity, radiant temperature and air velocity were recorded under free running mode. Along with objective measurements, a total of 113 girl students aged 15-18 were surveyed three times in the high school, 59 students during April 2015 and 54 students during October 2015, collecting a total of 323 questionnaires. Moreover, 59 girl students aged 10-11 were surveyed in the primary school during May 2014, collecting a total of 172 questionnaires. Results show that  $T_{op}$  is closer to  $T_{out}$  in the high school with courtyard design than in the primary school with compact design, especially in north facing classrooms where the effect of solar radiation is less. Furthermore, results of this study show that PMV model overestimates high school students' thermal sensation while overestimates children's thermal sensation at higher temperatures and underestimates it at lower temperatures.

**Keywords:** Thermal comfort, High School, Primary School, Design, Courtyard

### Introduction

Students have diverse activities during a day with limited adaptive actions in classrooms (Teli, Mark F Jentsch, et al. 2012) so their perception of thermal comfort may be totally different than that of occupants in an office. As a result, there is no guarantee that steady state heat-balanced model of thermal comfort obtained from experiments with adults (Fanger 1970) or adaptive model of thermal comfort developed from surveys in offices (Dear et al. 1998; Nicol & Humphreys 1973) can reliably represent student's perception of thermal comfort. Although several studies have considered thermal perception of children at schools (Humphreys 1977; Teli et al. 2014; Montazami et al. 2017; ter Mors et al. 2011; De Giuli et al. 2012), there are still fewer researches in hot-arid climates like Iran (Haddad et al. 2013; Haddad et al. 2016a; Zahiri et al. 2011), especially with regards to the effect of spatial configuration and design on thermal environment and thermal perception. In Iran, most school buildings have compact plans with poorly insulated envelopes and usually no external shadings while there are no regulations to control indoor temperature (Zomorodian & Nasrollahi n.d.). That results in

overheated schools in summers and sometimes even in spring and fall. Therefore, the main objectives of the paper have been defined as follows:

- To study the impact of design on thermal environment in a school with courtyard design and in a school with compact plan design.
- To investigate the applicability of PMV model to predict primary school and high school students' thermal sensation votes.

## Methodology

The methods applied in the paper include both measurement of environmental variables and questionnaire surveys. The study is conducted in mid seasons, fall and spring, to make sure that no heating system or cooling system is in use in the school. The average temperature of Kashan is 19.2°C in April and 24.4°C in May (Anon n.d.) but there is a large difference between day and night temperature.

### ***Location, Building***

Case study buildings are located in Kashan, Iran ( $33^{\circ} 58' 59''$  N /  $51^{\circ} 25' 56''$  E) which is characterized with desert climate and clear-sky conditions, (Fig 1). The high school is chosen due to its design reminding Iranian traditional architecture with four south facing and four north facing classrooms surrounding a central courtyard, (Figs 1, 2 & 5). The studied primary school is located across the high school but with a typical compact design of schools in this region, (Figs 1 & 3). Schools have inclined 25 degree toward west and have North-West and South-East orientation, (Fig 1). As all the classrooms are the same in size and design, one south facing classroom and one north facing classroom have been selected in the middle of each school.

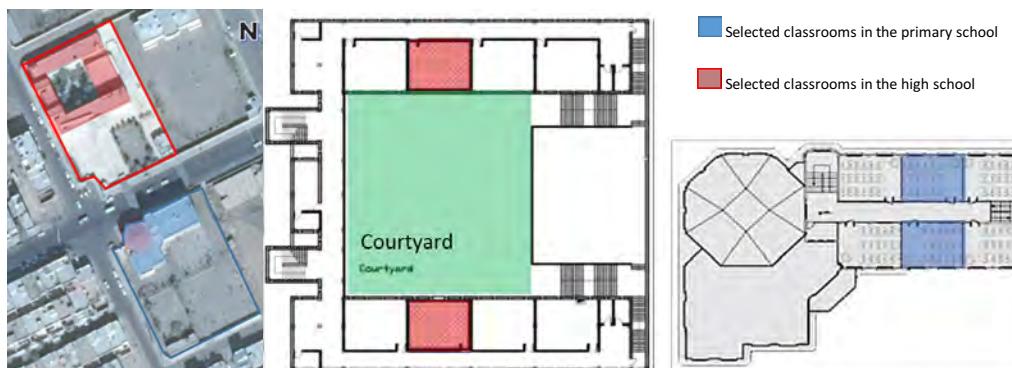


Fig 1. Left: location and orientation of the schools (Image from Google Earth). Fig 2. Middle: high school floor plan. Fig 3. Right: primary school floor plan

Both schools have medium thermal mass buildings with classrooms of approximately the same size, around  $50\text{ m}^2$ . High school classrooms are day-lit through 4 double glazed windows with 2.3 m height and 0.5 m width, WWR=20%, (Fig 4), and primary school classrooms are day-lit with 2 double glazed windows which cover 21% of the wall, without external shadings, (Fig 6).



Fig 4. Left: high school. Fig 5. Middle: high school's Courtyard. Fig 6. Right: primary school

### **Subjective Measurements**

A total of 113 girl students aged 15-18 were surveyed three times in the high school, 59 students from 20-22 April 2015 and 54 students from 19-21 October 2015, collecting a total of 323 questionnaires. 59 students aged 10-11 were surveyed in the primary school during 5-7 May 2014, collecting a total of 172 questionnaires. Table 1 provides detailed information of the number of subjects. The schools' academic year start around September 25 and ends around June 18 and classrooms are occupied from Saturday to Wednesday, 8:00 to 14:30.

Table 1. Provides detailed information of the number of subjects

School	Season	Classroom Orientation	Number of Votes/Number of Students			
			1st day	2nd day	3rd day	Total
High School	Spring	South	30/30	30/30	28/30	88/90
		North	28/29	27/29	29/29	84/87
	Fall	South	26/26	26/26	24/26	76/78
		North	28/28	23/28	24/28	75/84
Primary School	Spring	South	28/29	28/29	29/29	85/87
		North	29/30	30/30	28/30	87/90

Prior to doing the main study in the high school, a group of 10 students were selected from each classroom to fill out a 7-point scale questionnaire in two successive days in spring at three different times, 9, 11 a.m. and 12:30 p.m. Based on feedback received from students and teachers, the questionnaire was long and confusing so it changed to a five point scale questionnaire in its second edition, (+2) Hot, (+1) Warm, (0) Neutral, (-1) Cool and (-2) Cold. For devising the appropriate questionnaire for children in the primary school, authors took into account several studies (Fabbri 2015; Teli, Mark F. Jentsch, et al. 2012; Haddad et al. 2012), yet, teachers checked the questions and commented on changing the 7-point scale questionnaire to a 5-point scale questionnaire, (+2) Hot, (+1) Warm, (0) OK, (-1) Cool and (-2) Cold. The questionnaires were administered only once in each three days but at different hours as students found it tiring to fill out questionnaires three times a day. Although the study by (Goto et al. 2002) shows that 15 min of sedentary activity enables the body to reach a stable thermal state, the surveys were handed out after 30 minutes of the classroom activity to provide a safety margin (Montazami et al. 2017; Teli, Mark F. Jentsch, et al. 2012).

Metabolic rate was considered 1.2 met as students were engaged in sedentary activity after half an hour of the start of the class. The clothing values were found to be within a range of 0.7 to 0.8 Clo; the Clo value is relatively high for spring and fall in this region which is due to Islamic regulations and dress code. Moreover, as schools are segregated and students are exposed to same cultural background and outdoor temperature (Haddad et al. 2016a), clothing patterns are not very different.

## Objective measurements

The environmental parameters were measured according to the standards of ISO 7726 (ISO 7726 2001) and simultaneous with physical measurements. Radiant temperature (globe thermometer with diameter=100mm), air temperature, relative humidity and air speed were measured by Testo data logger 175-H2, WBGT8778 and Testo flow meter at the height of 1.1 at the intervals of half an hour. To ensure acclimatisation to the classroom environment, instruments were set up an hour before experiment in the centre of the classrooms and away from sunlight patches. All measurements were done at sunny and clear days.

## Results

### *Students' perception of the questionnaire*

All replies were controlled in terms of inconsistency so that the cases with  $(TSV+TPV)<-3$  or  $(TSV+TPV)>+3$  are not reliable since a student feeling hot does not normally prefer a warmer environment (Teli, Mark F Jentsch, et al. 2012). The replies were all reliable, even in the primary school, which confirms students' good understanding of the questionnaires.

### *Students' thermal sensation and thermal preference vote*

Fig 7 shows the distribution of TPV in relation to TSVs at each classroom, with mean operative temperature for each orientation. Students mostly find their environment 'warm' in south facing classrooms, 51% in high school and 59% in primary school. Students mostly feel 'neutral' in north/high school (54%) and have close warm (38%) and neutral sensations (31%) in north/primary school which is due to higher mean operative temperatures ( $29.3^{\circ}\text{C}$ ), (Fig 7). TPVs are centred on cooler and colder with 83% in south/high school, 67% in north/high school, 87% in south/primary school and 95% in north/primary school. Students in both schools have a more neutral sensation towards north facing classrooms than south facing classrooms, especially in the high school where the difference between operative temperature in north and south facing classrooms is higher than in the primary school. This can be attributed to the special design of this school with the courtyard in centre.

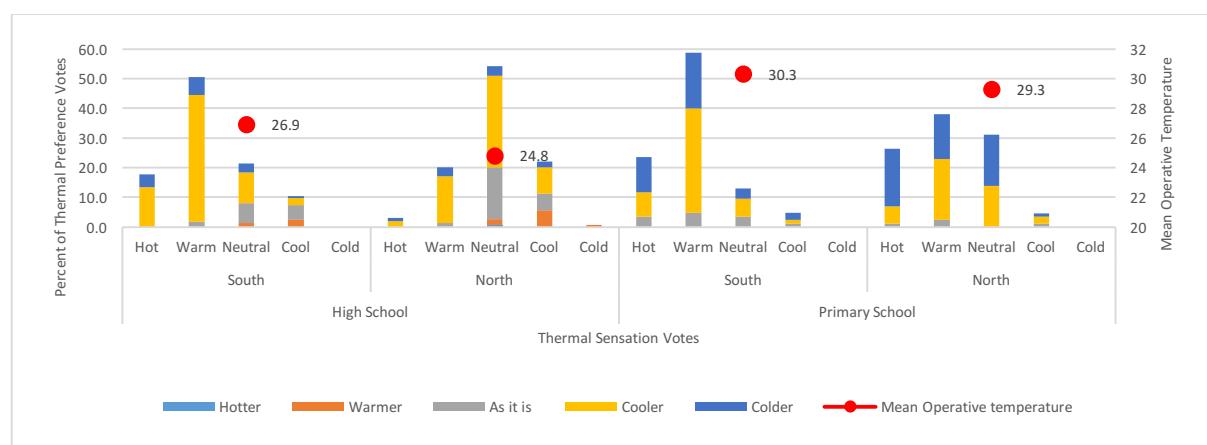


Fig 7. Relative Frequency of TSV against TPV and operative temperature

### *Effect of School Design on thermal Environment*

As floor area, WWR, thermal mass and the number of students in each classroom are approximately the same, studying the effect of design on operative temperature and thermal environment is more controlled. By referring to Table 2, it can be seen that  $T_{op}$  is closer to  $T_{out}$

in high school with the courtyard design than in primary school with compact design, especially in north facing classrooms where the effect of solar radiation is less. In the high school,  $T_{op}$  is averagely 11% higher than  $T_{out}$  in S/spring, 4% higher in N/spring, 9% higher in S/fall, 1% higher in N/fall. In the primary school, this difference is more significant, with  $T_{op}$  being 18% higher than  $T_{out}$  in S/spring and  $T_{op}$  being 16% higher than  $T_{out}$  in N/spring. The difference between  $T_{op}$  and  $T_{out}$  in the primary school is 1.6 times and 4 times higher than that in the high school in south and in north facing classroom, respectively. The courtyard design provides more shaded areas and wall surfaces with lower temperatures which can reduce indoor temperature. The effect of wall surfaces on indoor temperature has already been verified by (Rajapaksha et al. 2003) which also points to the importance of courtyards on optimizing natural ventilation to minimize indoor overheating. The study by (Taleghani et al. 2014) has also suggested that designing a courtyard in severest climate scenario, can provide an optimum balance between energy use and summer comfort (May to October). Another paper by (Taleghani et al. 2015) shows that the courtyard can provide the most comfortable microclimate in the Netherlands in June.

### **Comparison of PMV-TSV**

To provide criteria for thermal comfort based on the PMV indices, environmental parameters including ambient air temperature, mean radiant temperature, air velocity and relative humidity were measured and clothing insulation and metabolic rate were also estimated while doing surveys (Fanger 1970). For PMV calculations, ASHRAE Standard 55 (Ansi/Ashrae 2013) equations were used. Table 2 shows the results from the field measurements (TSV, TPV and SD), PMV Predictions,  $T_{out}$  and calculated  $T_{op}$ , with highlighted rows for those that don't comply with ASHRAE 55 PMV method and estimate slightly warm or warm sensation.

There are not large variations within TSVs, with the standard deviation ranging from 0.52 to 0.89 in the high school and 0.66 to 1.18 in the primary school. S.D. <sub>mean</sub> for the primary school is 0.8 which is smaller than the mean value of 1.07 based on studies done by (Humphreys et al. 2007). Although there is not high variation in TSVs but S.D. <sub>mean</sub> in the primary school, 0.8, is higher than that in the high school, 0.7, which can be attributed to children's higher metabolic rate and more diverse activities in the schedule. This finding has been confirmed by (Teli, Mark F Jentsch, et al. 2012).

Table 2. Presents Operative temperature, PMV, TSV and TPV of all surveys.

Stage	Orientation/Season	$T_{out}$	$T_{op}$	PMV	TSV	SD <sub>TSV</sub>	TPV	SD <sub>TPV</sub>	PMV	Sensation
High School	S/Spring	23.1	25.5	0.4	0.20	0.89	-0.83	0.53		Neutral
		23.8	26.9	0.74	0.67	0.61	-1.00	0.37	x	Slightly warm
		25.2	29.2	1.27	1.32	0.77	-1.35	0.49	x	Slightly warm
	N/Spring	23.1	24.7	0.22	-0.18	0.77	-1.00	0.72		Neutral
		23.8	25	0.27	0.11	0.80	-0.93	0.55		Neutral
		25.2	25.9	0.49	0.55	0.63	-1.00	0.50		Neutral
	S/Fall	22.1	25.4	0.44	0.00	0.69	-0.15	0.78		Neutral
		24.2	26.9	0.87	1.10	0.52	-1.10	0.39	x	Slightly warm
		26.8	27.6	1.06	1.33	0.64	-1.16	0.56	x	Slightly warm
	N/Fall	22.1	24	0.12	-0.21	0.69	-0.11	0.83		Neutral
		24.2	24.7	0.32	-0.17	0.58	-0.26	0.86		Neutral
		26.8	24.7	0.35	0.04	0.81	-0.58	0.72		Neutral
Primary School	S/Spring	24.7	30.5	1.89	0.93	0.81	-1.11	0.69	x	Warm
		25.3	31	2	1.18	0.77	-1.32	0.77	x	Warm
		27.3	29.5	1.63	0.93	0.65	-1.28	0.53	x	Warm
	N/Spring	23.7	29.5	1.63	0.66	0.94	-1.21	0.62	x	Warm
		24.3	30	1.76	1.07	0.91	-1.8	0.48	x	Warm
		26.3	28.5	1.38	0.86	0.71	-1.43	0.50	x	Slightly warm

Fig 9 shows the actual mean TSV against the calculated PMV. The correlation between TSV and PMV in the primary school ( $R^2=0.40$ ) is not as strong as the correlation between TSV and PMV in the high school ( $R^2=0.92$ ), meaning that thermal condition that is assessed by PMV Index is more reliable for high school students than for children in this study. The correlation between TSV and PMV in the primary school is very close to the correlation found in the study done by (Teli, Mark F Jentsch, et al. 2012).

Fig 10 shows the relationship between TSVs and PMVs plotted against  $T_{op}$  and linear regressions for both primary and high school which have the following equations, respectively:

$$\text{Equation 1: } TSV_{(mean)} = 0.3652 T_o - 9.0544, R^2 = 0.88,$$

$$\text{Equation 2: } TSV_{(mean)} = 0.13T_o - 2.94, R^2 = 0.40'$$

According to equation 1, TSV in the high school remains close to neutral, between +0.5 and -0.5, when the operative temperature is between 23.7°C and 26.5°C and PMV is close to neutral when the operative temperature is between 21.4°C and 25.9°C. PMV slightly overestimates students' thermal sensation in the high school while they can tolerate higher temperatures. Most of PMV points fall a little above those of TSV in the high school or are very close to TSV points but TSV is slightly higher than PMV at higher temperatures, more than 27°C, which shows students sensitivity to higher temperatures.

According to equation 2, primary school students' TSV is close to neutral sensation, when the operative temperature is between 18.7°C and 26.4°C, and PMV is close to neutral when the operative temperature is between 20.9°C and 24.9°C, meaning that children accept a wider range of temperatures than what has been suggested by PMV model and feel less sensitive to temperature variations. Although all PMV points fall above those of TSV in the primary school, Fig 11, it cannot be concluded that PMV overestimates children's thermal perception as, first, graphs and equations show that at lower temperatures, PMV model would underestimate children's perception, second, the number of students are not large enough to draw any firm conclusion. According to the results derived from this study, it can be assumed that while PMV model underestimates children's thermal perception at low temperatures, it overestimates children's thermal sensation at high temperatures. Generally, the range proposed by PMV is much more limited than the range accepted by children in this study. While children tolerate lower temperatures than high school students, upper threshold of neutral temperature for them (26.4°C) is very close to that for adults (26.5°C) in this study and is higher than PMV predictions.

The correlation between TSV and  $T_{op}$  is quite satisfactory for the high school with  $r^2=0.88$  showing that students' mean sensation of thermal conditions is greatly affected by operative temperature variations. The regression gradient of 0.36 derived from this study is very close to the mean value derived from the study by (Humphreys et al. 2007) for adult subjects which is 0.37 scale unit/ $^{\circ}\text{C}$ . On the other hand, the correlation found between  $T_{op}$  and  $TSV_{(mean)}$  in the primary school is less satisfactory ( $r^2=0.4$ ). The low regression gradient of 0.13 shows that children are less sensitive to temperature changes which agrees with the studies done by (Teli, Mark F Jentsch, et al. 2012; Humphreys 1977). The derived value, 0.13, is lower than the value in the studies by (Teli, Mark F Jentsch, et al. 2012; Haddad et al. 2016b) which is 0.27.

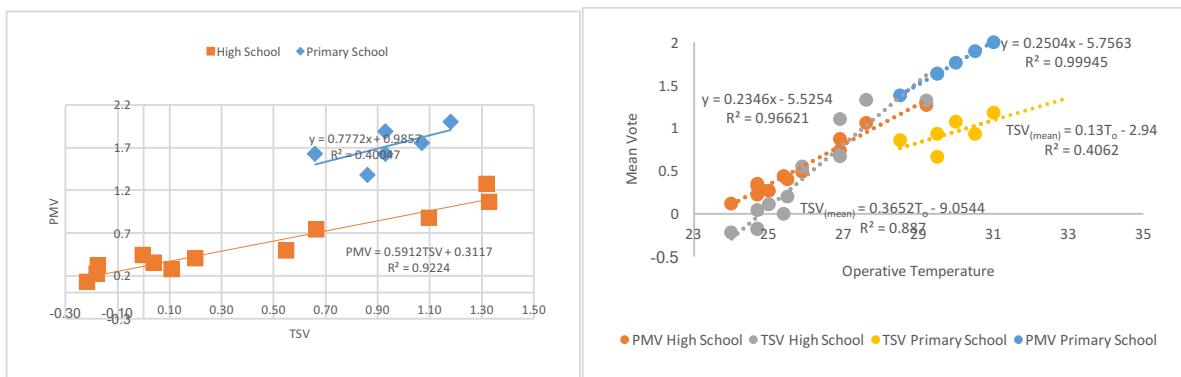


Fig 9. Left: TSVs by PMV. Fig 10. Right: TSV and PMV plotted against  $T_{op}$

## Conclusion

Results show that north facing classrooms provide lower temperatures and students' votes are more close to neutral in north facing classrooms. Moreover,  $T_{op}$  is closer to  $T_{out}$  in the high school with the courtyard design than in primary school with compact design, especially in north facing classrooms where the effect of solar radiation is less. Courtyard design can provide higher levels of natural ventilation and reduce overheating in this region.

Results show that PMV overestimates high school students' perception of comfort; TSV is lower than PMV in 8 out of 12 surveys and is higher than PMV only in high temperatures. According to the findings of this study and equation 2, PMV model also overestimates children's thermal sensation at high temperatures and underestimates it at low temperatures. A wider range of neutral temperatures are accepted by children ( $18.7^{\circ}\text{C} \leq T_n \leq 26.4^{\circ}\text{C}$ ) than that suggested by PMV ( $20.9^{\circ}\text{C} \leq T_n \leq 24.9^{\circ}\text{C}$ ) while many studies have confirmed that rational thermal comfort model underestimates children's thermal perception (Teli, Mark F Jentsch, et al. 2012; Montazami et al. 2017; ter Mors et al. 2011; Zeiler & Boxem 2009; Liang et al. 2012; Haddad et al. 2016b). The wider range of neutral temperature for primary school students than that by PMV model suggests that the physiology of children in this study can well adapt to wide outdoor temperature changes. Children' adaptability to lower temperatures can be justified by their higher metabolic rate and activity level as already confirmed by (Haddad et al. 2016b; Teli, Mark F Jentsch, et al. 2012; Montazami et al. 2017) and children' adaptability to higher temperatures can be justified by their expectations of the region. Moreover, higher PMV points than TSV points at high temperatures can also be attributed to the high mean value of Clo in this study (0.75) which results in high PMV values. As girl students have to follow dress codes and cannot take much adaptive behaviours towards clothing due to Islamic regulations, especially in mid-seasons, other behavioural and environmental behaviours should be provided and encouraged, especially for young children.

## References

- Anon, Chaharmahal Weather Station Website. Available at: <http://www.chaharmahalmet.ir/stat/archive/iran/esf/KASHAN/38.asp>.%22.
- Ansi/Ashrae, 2013. *ANSI/ASHRAE 55:2013 Thermal Environmental Conditions for Human Occupancy*.
- Dear, R. De et al., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104(Part 1), pp.1–18. Available at: <https://escholarship.org/uc/item/4qq2p9c6.pdf>%5Cn[http://repositories.cdlib.org/cedr/cbe/ieq/deDear1998\\_ThermC omPref](http://repositories.cdlib.org/cedr/cbe/ieq/deDear1998_ThermC omPref).
- Fabbri, K., 2015. *Indoor thermal comfort perception: A questionnaire approach focusing on children*,
- Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. ... *comfort Analysis and applications in environmental* .... Available at: <http://www.cabdirect.org/abstracts/>

19722700268.html%5Cnpapers2://publication/uuid/5CE163C3-F9AC-4937-A143-1238F1D806C5.

De Giuli, V., Da Pos, O. & De Carli, M., 2012. Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment*, 56, pp.335–345.

Goto, T., Toftum, J. & Dear, R. De, 2002. Thermal sensation and comfort with transient metabolic rates. , (1966), pp.1038–1043.

Haddad, S. et al., 2012. Questionnaire Design to Determine Children's Thermal Sensation, Preference and Acceptability in the Classroom. *28th Conference, Opportunities, Limits and Needs Towards an environmentally responsible architecture*, 1(November), p.2.

Haddad, S., Osmond, P. & King, S., 2013. Metabolic rate estimation in the calculation of the pmv for children. , pp.241–250.

Haddad, S., Osmond, P. & King, S., 2016a. Revisiting thermal comfort models in Iranian classrooms during the warm season. *Building Research & Information*, 3218(February), pp.1–17. Available at: <http://www.tandfonline.com/doi/full/10.1080/09613218.2016.1140950> [Accessed November 3, 2016].

Haddad, S., Osmond, P. & King, S., 2016b. Revisiting thermal comfort models in Iranian classrooms during the warm season. *Building Research & Information*, pp.1–17. Available at: <http://www.tandfonline.com/doi/full/10.1080/09613218.2016.1140950> [Accessed November 3, 2016].

Humphreys, M.A.A., 1977. A study of the thermal comfort of primary school children in summer. *Building and Environment*, 12(4), pp.231–239. Available at: <http://www.sciencedirect.com/science/article/pii/0360132377900257>.

Humphreys, M. a. et al., 2007. Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach. *Advances in Building Energy Research*, 1(May 2013), pp.55–88.

ISO 7726, 2001. *Ergonomics of the thermal environment — Instruments for measuring physical quantities*,

Liang, H.H., Lin, T.P. & Hwang, R.L., 2012. Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. *Applied Energy*, 94, pp.355–363. Available at: <http://dx.doi.org/10.1016/j.apenergy.2012.02.004>.

Montazami, A. et al., 2017. Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms. *Building and Environment*, 111, pp.61–71. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0360132316304012>.

ter Mors, S. et al., 2011. Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Building and Environment*, 46(12), pp.2454–2461.

Nicol, J.F. & Humphreys, M.A., 1973. Thermal comfort as part of a self-regulating system. *Building Research and Practice*, 1(3), pp.174–179.

Rajapaksha, I., Nagai, H. & Okumiya, M., 2003. A ventilated courtyard as a passive cooling strategy in the warm humid tropics. *Renewable Energy*, 28(11), pp.1755–1778.

Taleghani, M. et al., 2015. Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and Environment*, 83, pp.65–78.

Taleghani, M., Tenpierik, M. & van den Dobbelaer, A., 2014. Energy performance and thermal comfort of courtyard/atrium dwellings in the Netherlands in the light of climate change. *Renewable Energy*, 63, pp.486–497. Available at: <http://dx.doi.org/10.1016/j.renene.2013.09.028>.

Teli, D., Jentsch, M.F., et al., 2012. Field study on thermal comfort in a UK primary school. *Proceedings of 7th Windsor Conference: The changing context of comfort in an unpredictable world Cumberland Lodge, Windsor, UK*, 7730(April), pp.12–15.

Teli, D., Jentsch, M.F. & James, P.A.B., 2012. Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings*, 53, pp.166–182. Available at: <http://dx.doi.org/10.1016/j.enbuild.2012.06.022>.

Teli, D., Jentsch, M.F. & James, P.A.B., 2014. The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies. *Building and Environment*, 82, pp.640–654. Available at: <http://dx.doi.org/10.1016/j.buildenv.2014.10.005>.

Zahiri, S., Sharples, S. & Altan, H., 2011. Developing sustainable school design in Iran thermal comfort survey of a secondary school in Tehran. In *Passive Low Energy Architecture, Belgium*. Belgium., pp. 523–538.

Zeiler, W. & Boxem, G., 2009. Effects of thermal activated building systems in schools on thermal comfort in winter. *Building and Environment*, 44(11), pp.2308–2317.

Zomorodian, Z.S. & Nasrollahi, F., Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran. *International Journal of Architectural Engineering & Urban Planning*, 23(2).



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*Design to Thrive*

## Thermal design, climate change and human evolution: The evolutionary costs of comfort in artificial environments on human health

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**Abstract:** The present paper represents the proposal of a line of research whose objective is to explore the importance of build environment in human health and cognitive expression from an interdisciplinary point of view in order to improve the design of human habitat explaining the evolutionary function of environmental diversity and providing evidence of the risk represented by climate change and artificial environments (more specifically, thermal monotony and permanent lighting) due to the evolutionary capacity of homeotherms to respond to environmental changes by triggering responses in cognitive plasticity, whose biological function is to increase the chances of survival under environmental threats but it could also pose a health risk when activated by false signals in artificial environments. In humans this hypothesis is supported by the evidence of the interrelation between plasticity and environmental information in the fields of evolution and epigenetics, as well as evidence of positive selection of alleles linked to Schizophrenia, Autistic Spectrum Disorders (ASD) and Attention Deficit Hyperactivity Disorder (ADHD).

**Keywords:** Evolution, thermal environments, ADHD, ASD, Schizophrenia

### Introduction

The idea that the only way to access to comfort is through thermal monotony was formalized more than a century ago with the implementation of the first artificial climate control system and the publication of the *Rational Psychrometric Formulae* (Carrier, 1911).

Even today, despite the lack of scientific evidence and regardless its high economic, energetic and environmental costs, the main goal of HVAC systems is the elimination of any perceptible oscillations throughout the day and seasons (e.g. de Dear, 2014). The challenges posed by climate change and the possibility of improving comfort through thermal diversity allow us to reconsider the role of oscillations in health and human evolution because even if it is practically impossible to design a comfort model capable of abstracting the wide systems of the thermal response, the understanding of its practical and evolutionary function could be fundamental to avoid the mistakes committed decades ago in other fields of human knowledge, by recognizing that the most comfortable is not always the healthiest.

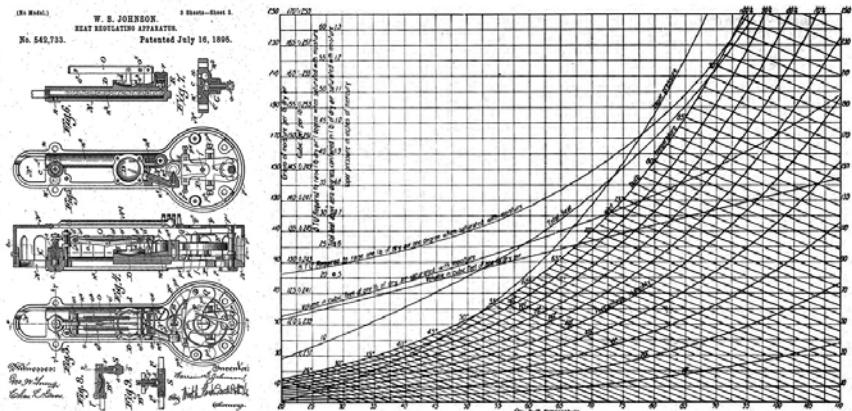


Figure 1. The beginnings of contemporary thermal control. Patent for a household thermostat, granted to Warren S. Johnson; Heat Regulating Apparatus; US 542,733, 1895. Psychrometric Chart; Carrier, 1911.

### The environment as a source of evolutionary information

Until recently, the original argument according to which the savannah was the setting in which humans have evolved since their separation from the rest of the hominids was universally accepted. However, recent contributions in physiology (e.g. Carrier 1984; Wrangham et al, 1999) and paleoclimatic reconstruction (e.g. Petit et al, 1999) have made it evident that humans and all terrestrial organisms have evolved experiencing constant changes in their habitat. The constant habitat change, originated by the Milankovitch cycles (eccentricity, obliquity, and precession), gave rise to unpredictable trends and oscillations in insolation and temperature with profound effects on hydrology, landscape, and vegetation.

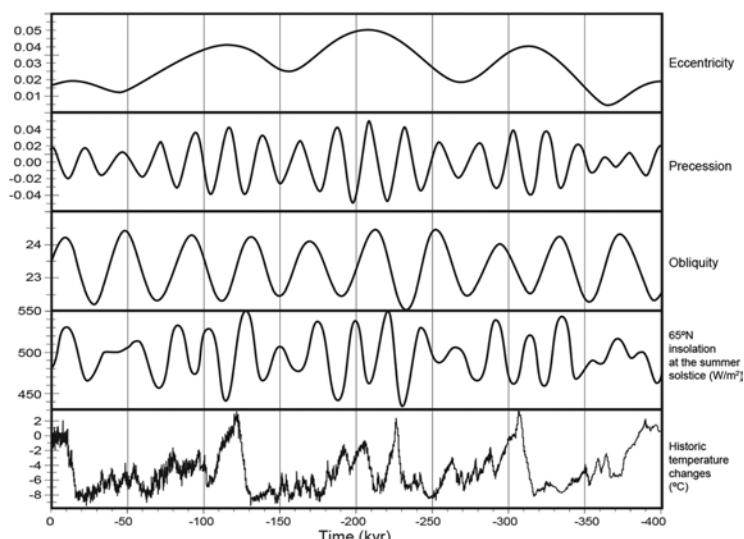


Figure 2. Oscillations in large-scale orbital cycles, temperature and calculated insolation for the last 400 thousand years at 65°N for the summer solstice. Based on Petit et al, 1999 and Berger et al, 2016.

The resulting climatic variability represents a possibility of unification in evolutionary history (Potts & Faith, 2015) because it allows us to reconceptualise human morphological, physiological and behavioural characteristics as evolutionary responses to face the most demanding climatic changes (Grove, 2012). In the last thousand years, these climatic changes not only allowed the expansion of humans across continents but also gave direction to the genetic expression of the most convenient alleles to cope with these factors (Jablonski et al, 2012). This leads to consider the substantial differences between populations as adaptations to latitude, solar radiation, temperature and relative humidity (Hancock et al, 2011). Those

adaptations were made possible by the optimization of the sensitive collectors and the processors of environmental data (Potts 1998; Sangster et al, 2004) represented by thermal and light perception systems (e.g. TRP channels and thermoreceptors) to distinguish and respond to environmental threats.

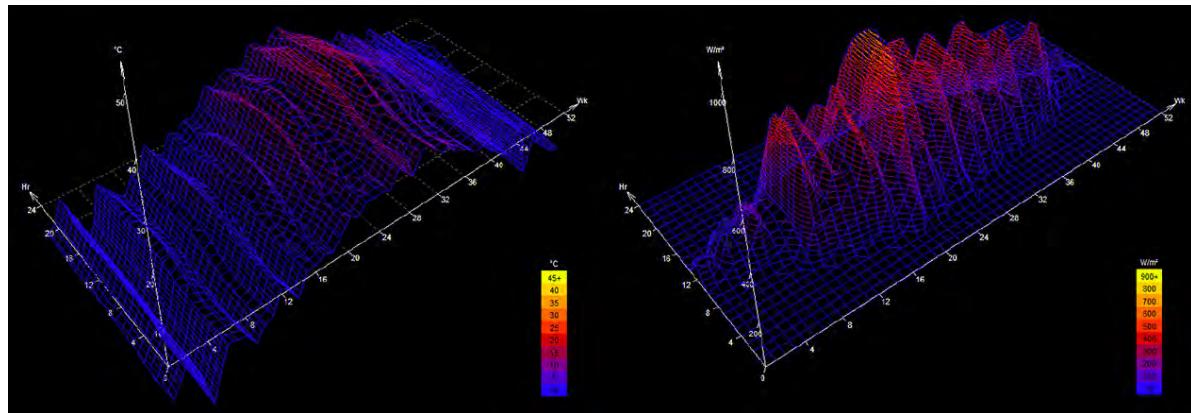


Figure 3. Variation in average temperature ( $^{\circ}\text{C}$ ) and direct solar radiation ( $\text{W}/\text{m}^2$ ) near to  $65^{\circ}\text{N}$ . Östersund.

While the influence of environment on organisms is the result of evolutionary processes that play out over extended periods of time rather than in “exact instants”, the means of adaptive flexibility that evolved through variability selection could be decoupled from any specific set or range of environments (Potts, 1998) as a possibility of novel response to adaptive problems. This implies that a single signal or a group of relevant environmental signals have the capacity to activate the available genetic pool to give way to new phenotypes (Potts & Faith, 2015), explained by the interrelated notions of *robustness*, *evolvability* and *evolutionary capacitance* (Grove, 2014), more specifically, through the action of the most important proteins for thermal protection and epigenetic modification: the Heat Shock Proteins (HSPs).

### Cognitive plasticity and Heat Shock Proteins

Since a species like the human, with a very little phenotypic variation, may be well adapted to a stable environment in the short term, but could be unable to respond to a sudden change in the environment (Masel, 2005), there are genetic mechanisms that increase its phenotypic variation and the most effective one is the combination of the available gene pool.

In humans, the most susceptible responses to environmental influence are those related to cerebral plasticity (Barry & Mattick, 2012), more specifically, to endocrine systems (Bateson, 2012), neural communication (Shumay et al, 2010) and behaviour in general (Badyaev, 2005). The most effective way to access to them is through the HSPs, whose epigenetic action allows access to a wide variety of preexisting genetic polymorphisms distributed elsewhere in the genome (Queitsch et al, 2002; Sangster et al, 2004). Among those polymorphisms, those that increase the variability of response in humans are related to psychiatric disorders that have been favoured by positive selection (e.g. Crespi et al, 2007; Lo et al, 2007; Shumay et al, 2010).

Since the main function of Heat Shock Proteins is to protect cells from environmental threats, they respond to immediate thermal information with changes that depend on factors associated with the season of the year (Feder & Hofmann, 1999). Therefore, a change in normal climate cycles can trigger responses that concern not only thermoregulatory system but also gene expression in its entirety, since HSPs are both thermal protectors and

chaperones (*i.e.* they contribute to correct synthesis of other proteins). Consequently, HSPs have the ability to trigger genetic responses as a source of evolutionary innovations (Queitsch et al, 2002; Masel, 2006), which explains the capacity of environmental information to modify gene expression and emphasizes the urgency of studying the correlation between human adaptation and climate change of anthropogenic origin, whose speed far exceeds the records of any previous change.

In other words, Heat Shock Proteins function as evolutionary capacitors (in analogy with electric capacitors) whose aim is to free the *charge* of accumulated but invisible combinations in the gene pool (called *cryptic variants*, Sollars et al., 2003), in order to increase *evolvability* (Pigliucci, 2008), which is defined as the rate of appearance of heritable and potentially adaptive phenotypic variants to enhance the chance of success in facing environmental threats (*e.g.* glaciation or drought) that would compromise the availability of critical resources.

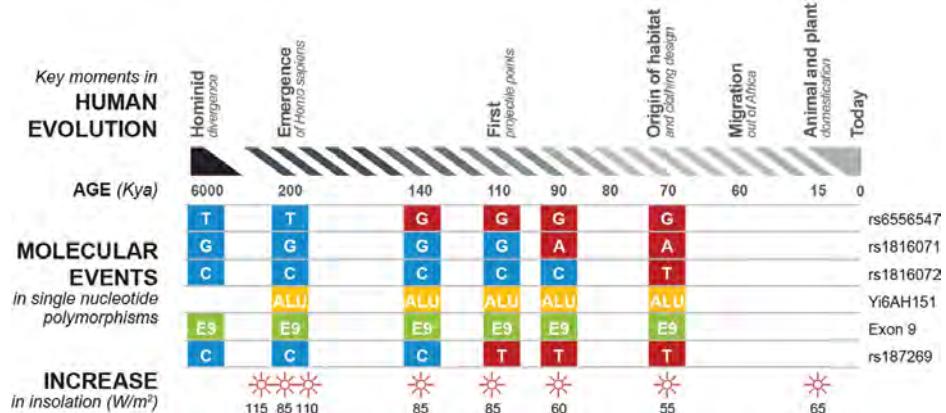


Figure 4. The historical success of human cognitive plasticity triggered by changes in the environment is evident in the coincidence between human innovation, solar insolation changes, and molecular evolution events in GABA system linked to psychiatric disorders. Based on data from Lo et al, 2007 and Berger, 2016.

Even the synthesis and reuptake of monoamine neurotransmitters, such as dopamine and serotonin, naturally change throughout the day and year (*e.g.* Ferris et al, 2011), implying that they are part of this complex system whose function has been, for hundreds of thousands of years, the maintenance of the balance between environmental changes and human responses. It follows that the suppression of thermal and light oscillations through artificial systems could constitute the greatest environmental change that humans have had to face since it represents a signal that the organism would decode as a huge threat, such as the one involved in an abrupt glacial period.

The behavioural and cognitive response to such a threat should be immediate in order to ensure survival. This can be achieved through the most accessible route, that is cognitive plasticity represented by the psychiatric disorders, whose original function in a stable environment —such as the present for the last 10ka years— is not only ineffective but counterproductive in view of the fact that more plastic phenotypes are at a disadvantage in more stable environments (Potts, 1998; Masel & Trotter, 2010; Potts & Faith, 2015).

### Gestation and environmental risk

The reading pathways of this environmental response system are integrated both by environmental readers (*e.g.* thermoreceptors, TRP ion channels) and environmental interactions (*e.g.* vitamin D deficiency, changes of circadian rhythms, and even stress). Consequently, the triggering effect of environmental information is especially significant during the gestational period since the maternal thermoregulatory system regulates the

embryo's HSPs, the first proteins expressed during the embryogenesis which fundamental role is to protect the embryo during its development (Hamdoun & Epel, 2007).

In fact, there is evidence linking maternal influenza and the rise in births of individuals who later developed schizophrenia (e.g. Watson, 1999), with an increased risk from three to seven times if the disease occurred during the second trimester (Edwards, 2007). This incidence could be not due to the infectious exposure, but rather to the increment in the temperature of the mother by febrile reaction (Lin et al, 2014), as confirmed by the capacity of elevated but stable thermal environments to rise the expression of genes related to schizophrenia and autism through stem cells models.

Through the use of Induced Pluripotent Stem Cells (iPSCs), it has been shown that prenatal exposure to environmental threats that augment HSPs synthesis can also increase the risk of expressing schizophrenia (Hashimoto-Torii et al, 2014). Even moderate and stable exposure to an ambient temperature of only 39°C for a period of 24 hours activates genes associated with a broad spectrum of psychiatric disorders, such as schizophrenia, autism, bipolar disorder and severe depression. Among the genes expressed during the second month of embryo development, there are regulators of GABA transporters, as well as serotonin and dopamine receptors, and various subtypes of nicotinic cholinergic receptors (Lin et al, 2014).

While it is impossible for the body temperature to remain unchanged at 39°C due to the thermoregulatory system, it shows that the possibility of keeping the temperature stable and monotonous for a very short time could trigger the process that results in cognitive plasticity as a way to prepare the organism to face an environment that undergoes profound changes. On the one hand, this explains why patients with schizophrenia and ADHD express fundamentally different thermal responses (e.g. Shiloh et al, 2001) and, on the other hand, why patients with schizophrenia present higher rates of HSPs (e.g. Kowalczyk et al, 2014).

Moreover, in regards to the lighting environments there is evidence linking the risk of Autism Spectrum Disorders (ASD) and treatment with antidepressants (specifically SSRIs, Selective Serotonin Reuptake Inhibitors) during pregnancy as demonstrated by several studies that have replicated the results (e.g. Man et al, 2015).

SSRIs inhibit the serotonin transporter (SERT) which raises the availability of serotonin independently of the season, and this has the same effect of permanent artificial lighting that eliminates variations throughout the day and year. Recently, a committee of the American Psychiatric Association published a review demonstrating that bright light therapy is as effective as antidepressants in relieving depression, including Seasonal Affective Disorder (SAD) (Golden et al, 2005), which implies that artificial lighting environments may also pose a risk during gestation period due to their ability to transmit a false environmental signal.

The fact that the risk of suffering from depression can also be modified by artificial environments is due to the fact that it is an evolutionary strategy that functions as an environmental reading and decoding system, whose purpose is to regulate offspring plasticity, as well as to limit energy consumption and reduce reproductive availability as a response to environmental conditions that compromise the access to resources, such as winter or maternity (which in turn explains Seasonal Affective Disorder and postpartum depression). In fact, this would not be the only resource management strategy shared by species that have faced habitat instability; the menopause, shared exclusively by humans and cetaceans but absent in other primates, aims to raise the chances of survival of the group's offspring by reducing competition (Croft et al, 2017).

In summary, studies that prove both the ability of thermal environments and SSRIs to trigger cognitive plasticity represent, at the moment, the best support for the hypothesis

developed in this project: psychiatric disorders are evolutionary responses triggered by false environmental cues.

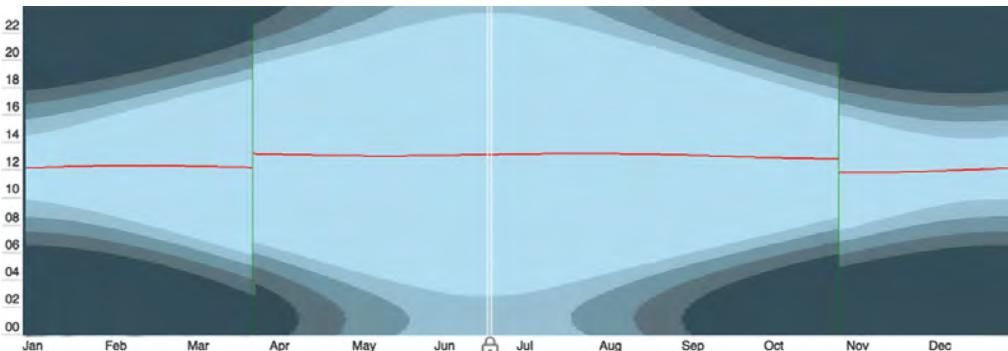


Figure 5. Solar insolation near to 65°N throughout the year. Östersund, Sweden. Both artificial lighting systems and antidepressant treatments with SSRIs modify the environmental signals by eliminating the seasonal effect on serotonin transporter. Image from timeanddate.com

## Conclusion

Although the impacts of climate change over the next 30 years are not considered an urgent threat to human health (Papworth et al, 2015), this point of view completely changes if we take into account that almost 50% of the world population lives in cities spending about 90% of time indoors (Andersen, 2015), and that even under modest assumptions, the fraction of households with HVAC systems will increase from the current 13% to more than 70% by the end of the century (Davis & Gertler, 2015) so that human health effects could actually be more immediate.

In this context, it is essential to understand the interaction between the artificial environments and humans, both in the framework of their evolutionary history and the individual response to the artificial environments, in order to provide answers not only with respect to comfort, but also with regard to its influence on health, as a possibility to reduce its negative effects and ensure the quality of life in an ever closer future.

Fortunately, nowadays there are several proposals that explore the possibility of improving comfort through thermal diversity (e.g. Huijzena et al, 2001; Nicol & Humphreys, 2002; de Dear, 2011; Auliciems, 2014), which allow us to rethink the role of thermal oscillations in human health and evolution. In fact, it is practically impossible to design a model of thermal comfort capable of abstracting the whole human thermal responses. However, the understanding of its practical and evolutionary function can be fundamental to avoid the wrong assumptions that have been maintained for decades as absolute truths in other fields of human knowledge when recognizing that, in most cases, the most comfortable turns out to be also the most harmful to health.

As confirmed by the medical sciences, after hundreds of thousands of years of human evolution, the healthiest remains the closest to the natural. Although it is impossible to suggest the elimination of artificial systems in all the latitudes of the world, it is undeniable that it is possible to adapt the HVAC patterns to daily and seasonal oscillations with an extension of the range, from the current 3°C (based on SET model) to 10°C (Evans, 2003), avoiding sudden changes with a rate maximum change in the air temperature of 1°C per hour (Fanger cited in Evans, 2007). This would imply great advantages not only for energy saving but also for health.

The same trend can be easily applied to lighting systems by implementing a dynamic design capable of incorporating both natural lighting and the combination of light

characteristics (temperature, intensity and exposure time) to reproduce the normal illumination patterns for each latitude, season and time of day, in order to maintain the patterns stored in the gene pool, thus preventing the triggering of plasticity by false signals interpreted as a modification in solar availability.

Although the incorporation of an interdisciplinary approach poses great challenges for research and enormous difficulties for design, it is a necessary advance for the configuration of a habitat compatible with human needs and it could lead to better understand the interaction between climatic factors and human cognitive responses, e.g. Season of Birth and schizophrenia (Auliciems et al, 1996; McGrath & Welham, 1999), solar intensity and ADHD (Arns et al, 2013), and habitat change and ASD (Magnusson et al, 2012).

This could represent an opportunity to bring together, in the same design objective, the efforts to reduce environmental damage, decrease costs of energy generation and improve human health, in order to face the challenges that climate change will pose in the next decades.

## References

- Andersen, M. (2015). Unweaving the human response in daylighting design. *Building and Environment*, 91, pp.101-117.
- Arns, M. et al. (2013). Geographic variation in the prevalence of ADHD: The sunny perspective. *Biological Psychiatry*, 74(8), pp.585-590.
- Auliciems, A. et al. (1996). The relationship between temperature and schizophrenia birthrates. *Schizophrenia Research*, 18(2-3), p.105.
- Auliciems, A. (2014). Thermal sensation and cell adaptability. *International Journal of Biometeorology*, 58(3), pp.325-335.
- Badyaev, A. V. (2005). Stress-induced variation in evolution: from behavioural plasticity to genetic assimilation. *Proceedings. Biological sciences / The Royal Society*, 272(1566), pp.877-886.
- Barry, G. & Mattick, J.S. (2012). The role of regulatory RNA in cognitive evolution. *Trends in Cognitive Sciences*, 16(10), pp.497-503.
- Bateson, P. (2012). The impact of the organism on its descendants. *Genetics Research International*, 2012.
- Berger, B. et al. (2016). Interglacials of the last 800,000 years. *Reviews of Geophysics*, 54(1), pp.162-219.
- Carrier, D.R. (1984). The Energetic Paradox of Human Running and Hominid Evolution. *Current Anthropology*, 25(4), pp.483-495.
- Carrier, W. (1911). Rational Psychrometric Formulae. *Journal of the American Society of Mechanical Engineers*, 33, pp.1311-1350.
- Crespi, B., Summers, K. & Dorus, S. (2007). Adaptive evolution of genes underlying schizophrenia. *Proceedings. Biological sciences / The Royal Society*, 274(1627), pp.2801-2810.
- Croft, D.P. et al. (2017). Reproductive Conflict and the Evolution of Menopause in Killer Whales. *Current Biology*, pp.1-7.
- Davis, L.W. & Gertler, P.J. (2015). Climate change could drive air conditioning to boost carbon emissions. *PNAS*, 112(19), pp.5962-5967.
- de Dear, R. (2011). Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*, 39(2), pp.108-117.
- de Dear, R., (2014). Thermal counterpoint in the phenomenology of architecture. A Psychophysiological explanation of Heschong's "Thermal Delight". In: *Plea2014*, Ahmedabad, **16 -18 December 2014**.
- Edwards, M.J. (2007). Hyperthermia in utero due to maternal influenza is an environmental risk factor for schizophrenia. *Congenital Anomalies*, 47(3), pp.84-89.
- Evans, J.M. (2007). *The Comfort Triangles: A New Tool for Biocliatc Desgin*. Technische Universiteit Delft.
- Evans, J.M. (2003). Evaluating comfort with varying temperatures: a graphic design tool. *Energy and Buildings*, 35(1), pp.87-93.
- Feder, M.E. & Hofmann, G.E. (1999). Heat-shock proteins, molecular chaperones, and the stress response: Evolutionary and ecological physiology. *Annual Review of Physiology*, 61(1), pp.243-282.
- Ferris, M.J. et al. (2014). Dopamine transporters govern diurnal variation in extracellular dopamine tone. *PNAS of USA*, 111(26), pp.E2751-9.

- Golden, R.N. et al. (2005). The efficacy of light therapy in the treatment of mood disorders: a review and meta-analysis of the evidence. *American Journal of Psychiatry*, 162(4), pp.656-662.
- Grove, M. (2012). Orbital dynamics, environmental heterogeneity, and the evolution of the human brain. *Intelligence*, 40(5), pp.404-418.
- Grove, M. (2014). Evolution and dispersal under climatic instability: a simple evolutionary algorithm. *Adaptive Behavior*, 22(4), pp.235-254.
- Hamdoun, A. & Epel, D. (2007). Embryo stability and vulnerability in an always changing world. *PNAS of USA*, 104(6), pp.1745-50.
- Hancock, A.M. et al. (2011). Adaptations to Climate-Mediated Selective Pressures in Humans. *PLoS Genetics*, 7(4).
- Hashimoto-Torii, K. et al. (2014). Roles of Heat Shock Factor 1 in Neuronal Response to Fetal Environmental Risks and Its Relevance to Brain Disorders. *Neuron*, 82(3), pp.560-572.
- Huizenga, C., Hui, Z. & Arens, E. (2001). A model of human physiology and comfort for assessing complex thermal environments. *Building and Environment*, 36(6), pp.691-699.
- Jablonski, N.G. (2012). Human skin pigmentation as an example of adaptive evolution. *Proceedings of the American Philosophical Society*, 156(1), pp.45-57.
- Kowalczyk, M. et al. (2014). Heat shock protein 70 gene polymorphisms are associated with paranoid schizophrenia in the Polish population. *Cell stress & chaperones*, 19(2), pp.205-215.
- Lin, M. et al. 2014. Heat shock alters the expression of schizophrenia and autism candidate genes in an induced pluripotent stem cell model of the human telencephalon. *PLoS ONE*, 9(4), pp.1-11.
- Lo, W.S. et al. 2007. Positive selection within the schizophrenia-associated GABA<sub>A</sub> Receptor b2 Gene. *PLoS ONE*, 2(5).
- Magnusson, C. et al. 2012. Migration and autism spectrum disorder: Population-based study. *British Journal of Psychiatry*, 201(2), pp.109-115.
- Man, K.K.C. et al. (2015). Exposure to selective serotonin reuptake inhibitors during pregnancy and risk of autism spectrum disorder in children. *Neuroscience and Biobehavioral Reviews*, 49, pp.82-89.
- Masel, J. (2005). Evolutionary capacitance may be favored by natural selection. *Genetics*, 170(3), pp.1359-1371.
- Masel, J. (2006). Cryptic genetic variation is enriched for potential adaptations. *Genetics*, 172(3), pp.1985-1991.
- Masel, J. & Trotter, M. V. (2010). Robustness and evolvability. *Trends in Genetics*, 26(9), pp.406-414.
- McGrath, J.J. & Welham, J.L. (1999). Season of birth and schizophrenia: A systematic review and meta-analysis of data from the Southern Hemisphere. *Schizophrenia Research*, 35(3), pp.237-242.
- Nicol, J.F. & Humphreys, M.A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), pp.563-572.
- Papworth, A., Maslin, M. & Randalls, S. (2015). Is climate change the greatest threat to global health? *Geographical Journal*, 181(4), pp.413-422.
- Petit, J.R. et al. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399, pp.419-436.
- Pigliucci, M. (2008). Is evolvability evolvable? *Nature reviews Genetics*, 9(1), pp.75-82.
- Potts, R. (1998). Variability Selection in Hominid Evolution. *Evolutionary Anthropology*, 7(3), pp.81-96.
- Potts, R. & Faith, J.T. (2015). Alternating high and low climate variability: The context of natural selection and speciation in Plio-Pleistocene hominin evolution. *Journal of Human Evolution*, 87, pp.5-20.
- Queitsch, C., Sangster, T. a & Lindquist, S. (2002). Hsp90 as a capacitor of phenotypic variation. *Nature*, 417(6889), pp.618-24.
- Sangster, T.A., Lindquist, S. & Queitsch, C. (2004). Under cover: Causes, effects and implications of Hsp90-mediated genetic capacitance. *BioEssays*, 26(4), pp.348-362.
- Shiloh, R. et al. (2001). Abnormal thermoregulation in drug-free male schizophrenia patients. *European Neuropsychopharmacology*, 11(4), pp.285-288.
- Shumay, E., Fowler, J.S. & Volkow, N.D. (2010). Genomic features of the human dopamine transporter gene and its potential epigenetic states: Implications for phenotypic diversity. *PLoS ONE*, 5(6).
- Sollars, V. et al. (2002). Evidence for an epigenetic mechanism by which Hsp90 acts as a capacitor for morphological evolution. *Nature genetics*, 33(1), pp.70-74.
- Watson, J.B. et al. (1999). Prenatal teratogens and the development of adult mental illness. *Development and Psychopathology*, 11(3), pp.457-66.
- Wrangham, R.W. et al. (1999). The Raw and the Stolen. Cooking and the Ecology of Human Origins. *Current Anthropology*, 40(5), pp.567-594.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Thermal Comfort in Public Housing Estates in High-density Cities under Near-extreme Summer Conditions

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**Abstract:** In Hong Kong, over 40% of the population reside in public housing estates and the majority of the occupants are elderly and people with disabilities, making them more vulnerable to extreme hot weather. Under near-extreme summer conditions, the poor conditions of thermal comfort is accentuated due to the high air temperature and exposure of solar radiation. The objectives of the present study is to examine the thermal comfort conditions in two common types of buildings in public housing estates in Hong Kong under typical and near-extreme summer conditions. Numerical modelling was used to obtain information about the PMV values and air temperature in the units of the two dwelling types. Results suggested that the level of thermal comfort varies across these two types of buildings. It was found that the more recent building type (Harmony) generally provides better thermal comfort in dwellings. It also exhibits smaller increase in thermal discomfort under near-extreme summer conditions in terms of maximum PMV values recorded. Further work will focus on identifying design parameters that are potentially influential to thermal comfort and the corresponding effect on energy consumption under different meteorological conditions, which will be incorporated into design recommendations in subsequent stage of the study.

**Keywords:** Thermal comfort, high-density cities, near-extreme summer, summer reference year

### Introduction

The compact living environment in high-density cities leads to deteriorating living quality and significantly affects the health and well-being of building occupants. Reduced ventilation in high-density urban environment was found to be associated with the transmission and spread of infectious diseases (Li et al., 2007). Cramped environment also causes thermal discomfort (Cheng and Ng, 2006), noise annoyance (Kang, 2001), and psychological stress (Kaplan, 2001).

Thermal comfort of indoor environment is particularly important to building occupants since overheating in buildings causes heat stress and even deaths if heat is accumulated (Roaf et al., 2009). The 2003 heatwave in Europe is one of the examples of how prolonged intense heat causes deaths in buildings (D'Ippoliti et al., 2010).

Under future climate change, the frequency, magnitude and duration of such intense heat is likely to increase, particularly in urban areas where urban heat island phenomenon exacerbates the impact of intense heat. In order to assess the thermal comfort conditions of indoor environment, a near-extreme meteorological data set, namely Summer Reference Year (SRY), was developed for the assessment of building environmental performance (Jentsch et al., 2015). Unlike Test Reference Year (TRY) and Typical Meteorological Year (TMY) which represent typical year conditions, the SRY represent the near-extreme summer conditions in the multi-year series, especially in sub-tropical climate where overheating is very common in buildings due to high temperature (Lau et al., 2017). It provides a dataset for estimating summer discomfort in naturally ventilated and free-running buildings.

In Hong Kong, over 40% of the populations reside in public housing estates with mostly vulnerable groups to extreme hot weather such as elderly, physically disabled, socially or economically deprived. While mechanical cooling is relatively common in Hong Kong, the high cost incurred still prevents them from using it to relieve the intense heat during extreme hot weather. As such, the design of residential units is of utmost importance for providing natural ventilation and improving thermal comfort.

The present study aims to employ the SRY meteorological data set to examine the thermal comfort conditions in two dwelling types of public housing estates in Hong Kong. Numerical modelling was used to obtain information about the indoor environmental conditions in the units of the two dwelling types. The effect of unit orientations is also discussed for these two dwelling types. Temporal variations in thermal comfort conditions are also investigated. Findings of the present study contribute to a better understanding of thermal comfort under near-extreme summer conditions and the identification of key design parameters for subsequent parametric study.

## **Methodology**

### ***Building Types***

Two common building types were selected for the present study. Trident (Figure 1, left) is a common building type in public housing estates in the mid-1980s to the early 1990s. It is characterised by the Y-shape building form and typically up to 35 storeys. There are generally 18 - 24 units per storey with a size of 32 - 44 m<sup>2</sup>. Harmony (Figure 1, right) emerged as a successor to Trident and it was still adopted in recent development of public housing estates. It generally has over 40 storeys with 16 - 18 units per storey. The unit size ranges from 16 - 51 m<sup>2</sup>. Both represent the typical high-density residential environment in Hong Kong.

### ***Experimental Setup***

Numerical simulation was performed using DesignBuilder v5, in which indoor environmental conditions were generated by the dynamic EnergyPlus v8.5 simulation engine. Generic models of the units were constructed in block level and further partitioned into zones with different activities allocated accordingly (Figure 2). Full-size windows without fitted air-conditioners or exhaust fans were carefully placed at a height of 1.8m based on the floor layout plans. Component blocks were then added on top of windows where the flat above extrudes for providing shading. To reduce the computational cost, only flats of the mid or top floors for each building type were constructed in detail, while the common areas and the rest of the building were represented by a single adiabatic component block.

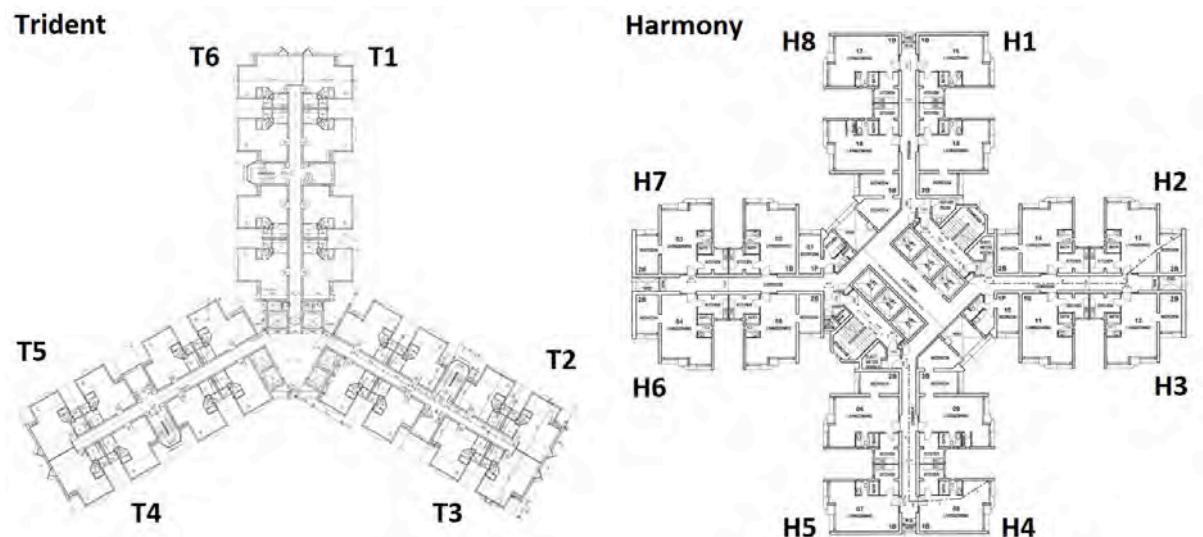


Figure 1. Building layout of Trident (left) and Harmony (right) types in public housing estates in Hong Kong.

The physical parameters of the modelled units were specified for the two building types in order to produce more accurate and realistic results. Construction materials were also determined according to current literature and practice (Table 1). Occupant density was assumed to be 0.083 person/m<sup>2</sup> based on the average living space per person of 12m<sup>2</sup> (Housing Authority, 2016). Simulations were set as free-running for each building type. No mechanical ventilation was applied and windows were assumed to remain open for 30% of the time.

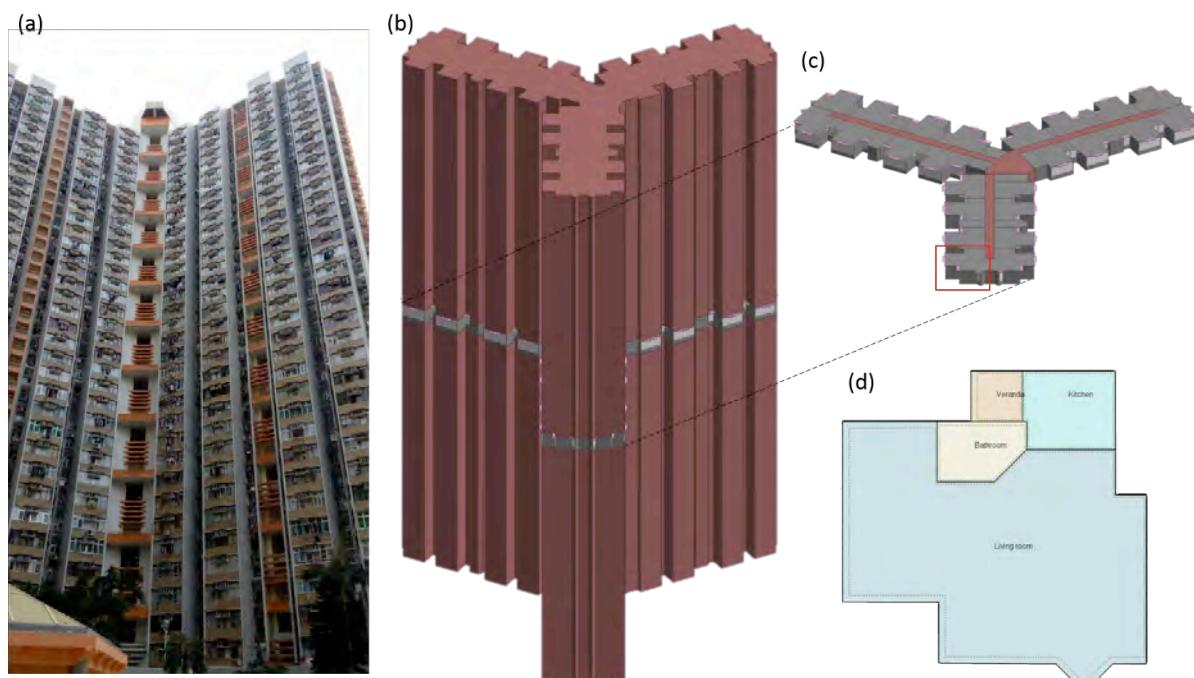


Figure 2. (a) On Chiu House (Trident type) in Cheung On Estate and generic models of (b) the whole building, (c) mid-floor flats and (d) a partitioned flat constructed in DesignBuilder.

Typical meteorological conditions are represented by using Test Reference Year (TRY; Levermore and Parkinson, 2006). The TRY of the Chartered Institution of Building Services Engineers (CIBSE) is composed of the most “typical” months from a meteorological dataset of at least 20 years. Near-extreme meteorological data representing critical summer conditions were used as the input meteorological conditions in the present study. Lau et al. (2017) utilised the SRY approach to develop a near-extreme summer meteorological data set for Hong Kong, consisting of meteorological data from April to September. Hourly outputs for summer months (June to August) were extracted and analysed for the thermal comfort conditions in different building types.

Table 1. The properties of building physical parameters, construction materials used in the present study.

	Trident	Harmony
<b><i>Building physical parameters</i></b>		
Floor height (m)	2.7	
Total occupied floor area ( $m^2$ )	920.6	670.5
Cooled area (i.e. living room, bedroom) ( $m^2$ )	731.2	506.2
Window-to-wall ratio	0.305	0.167
<b><i>Building construction</i></b>		
<b>External wall (outside to inside): U-value (<math>W\ m^{-2}\ K^{-1}</math>)</b>	3.33	2.88
- Mosaic Tile (mm)	5	
- Concrete Gypsum Plasterboard (mm)	10	
- Concrete (mm)	135	235
- Gypsum Plastering (mm)	13	
- Thermal conductivity ( $W\ m^{-1}\ K^{-1}$ )	0.532	0.749
<b>Roof: U-value (<math>W\ m^{-2}\ K^{-1}</math>)</b>	0.58	
- Asphalt Mastic Roofing (mm)	20	
- Expanded Polystyrene (mm)	50	
- Reinforced Concrete (mm)	200	
- Gypsum Plasterboard (mm)	13	
- Thermal conductivity ( $W\ m^{-1}\ K^{-1}$ )	0.164	
<b>Internal partition: U-value (<math>W\ m^{-2}\ K^{-1}</math>)</b>	2.86	
- Gypsum Plasterboard (mm)	10	
- Concrete (mm)	80	
- Gypsum Plasterboard (mm)	10	
- Thermal conductivity ( $W\ m^{-1}\ K^{-1}$ )	0.286	
<b>Floor slab: U-value (<math>W\ m^{-2}\ K^{-1}</math>)</b>	2.48	
- Floor Tiles (mm)	10	
- Reinforced Concrete (mm)	180	
- Gypsum Plasterboard (mm)	10	
- Thermal conductivity ( $W\ m^{-1}\ K^{-1}$ )	0.495	
<b>Glazing: U-value (<math>W\ m^{-2}\ K^{-1}</math>)</b>	5.75	
- Clear Float Glass (mm)	6	

### ***Indoor Thermal Comfort***

Indoor thermal comfort of the modelled units is described by air temperature (Ta) and Predicted Mean Vote (PMV; Fanger, 1972). Cheng and Ng (2006) defined the maximum acceptable air temperature as 29.5°C for naturally ventilated buildings during summer in

Hong Kong. The PMV model uses a seven-point scale from -3 to +3 to represent human thermal sensations from cold to hot. In accordance with the ISO7730, the calculation of PMV assumes a metabolic rate of 0.9 met and a clothing index of 0.3 clo in this study.

## Results and Discussion

### *Thermal Comfort in the Two Types of Buildings*

Figure 3 shows the summer mean PMV in the two building types modelled in the present study. In general, the PMV values of Trident are higher than those of Harmony, primarily due to the higher U-value of Trident units allowing faster heat transmittance. For Trident, the east- and west-facing façades show higher PMV values than the rest, slightly tilted orientations using both TRY and SRY data set. The corresponding values for the east- and west-facing façades under near-extreme summer conditions (SRY) are 1.78 and 1.70 respectively. The west-facing façade exhibits lower increase in maximum PMV shown by the difference between TRY and SRY data, particularly in the northwest-facing façade with an increase of 0.3 in maximum PMV value. It suggests that diagonally orientated, north-facing façades are able to reduce the discomfort under near-extreme summer conditions. Self-shading by the building itself is one of the important design strategies to minimize radiant heat gain and better design of site layout also contributes to the reduction of exposure to solar radiation.

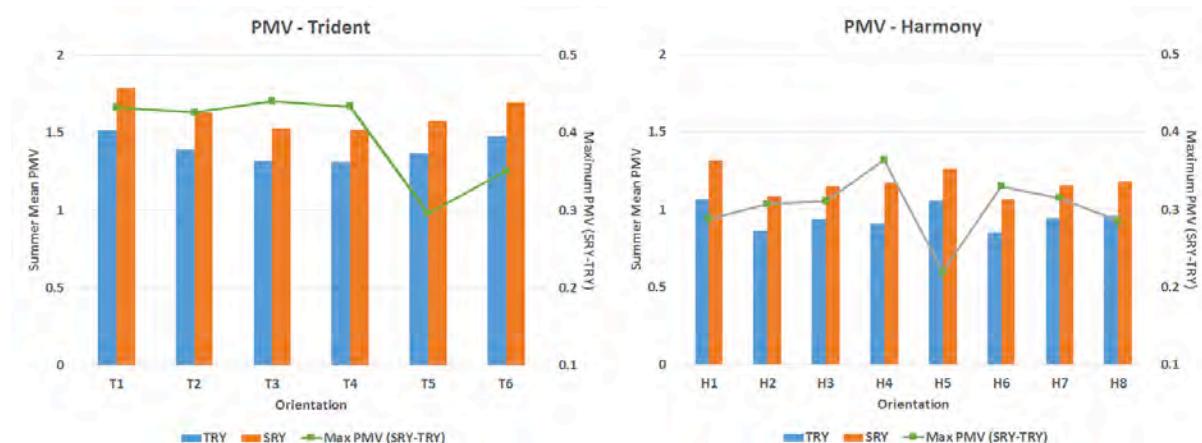


Figure 3. Summer mean PMV of different orientations for Trident (left) and Harmony (right) using TRY and SRY data. Line graph shows the difference in PMV between TRY and SRY.

Indoor air temperature was extracted to examine the overheating conditions of the modelled units. Table 2 shows the daily maximum indoor temperature ( $T_{max}$ ) in different orientations of the Trident units. It clearly shows that the east- (T1) and west-facing (T6) façades exhibit higher  $T_{max}$ , which is up to near 1°C higher than the south-facing units in July under the typical (TRY) scenario. Solar altitude is relatively lower when these units were sunlit so the level of solar radiation is more intense, resulting in higher thermal load in the units. Moreover, the highest increase in  $T_{max}$  under the near-extreme (SRY) scenario was observed in west-facing units (about 1.6°C higher than the TRY scenario). It implies that design features should be oriented to reducing the absorption of solar heat in these units.

Indoor  $T_{max}$  observed in the Harmony units is generally smaller than that in the Trident units. The differences between east- and west-facing units and other orientations are smaller in Harmony units (Table 3), suggesting that new design of public housing creates a

less variable indoor environment. The effect of near-extreme conditions is more prominent in August, with increase in indoor  $T_{max}$  ranging from 1.3-1.5°C. In addition, in both building types, indoor  $T_{max}$  under near-extreme summer conditions exceeds the threshold of very hot day warning issued by the Hong Kong Observatory (Hong Kong Observatory, 2016). It indicates potential heat stress experienced by building occupants under such overheating conditions.

Table 2. Daily maximum indoor temperature in the six orientations of Trident units during summer months.

Month	T1	T2	T3	T4	T5	T6
TRY	June	33.38	33.13	32.91	32.93	33.31
	July	33.46	33.10	32.76	32.75	33.13
	August	33.14	32.90	32.70	32.68	32.73
SRY	June	34.47	34.12	33.72	33.76	34.27
	July	34.40	34.17	33.85	33.85	34.55
	August	34.38	34.19	34.00	33.96	34.25

Table 3. Daily maximum indoor temperature in the six orientations of Harmony units during summer months.

Month	H1	H2	H3	H4	H5	H6	H7	H8
TRY	June	32.25	31.83	31.78	32.07	32.37	31.77	31.89
	July	32.46	31.99	31.98	32.28	32.72	31.95	32.04
	August	31.94	31.53	31.57	31.93	32.08	31.52	31.55
SRY	June	33.40	32.83	32.81	33.50	33.32	32.72	32.78
	July	33.28	32.72	32.69	33.10	33.41	32.65	32.74
	August	33.08	32.82	32.83	33.05	33.40	32.82	32.88

### Diurnal Variation of Indoor Air Temperature in Two Buildings

It was found that the orientation differs in the diurnal variation of indoor air temperature (Figure 4). For Trident units, east- and west-facing façades show higher indoor temperature than the rest of the façades with a diurnal range of about 2.4°C. Due to the high thermal conductivity of the Trident buildings, indoor temperature increases at a higher rate from sunrise to late-afternoon. Moreover, the east-facing unit exhibits higher indoor temperature (about 0.5°C) in the morning due to the exposure to solar radiation at low solar altitude.

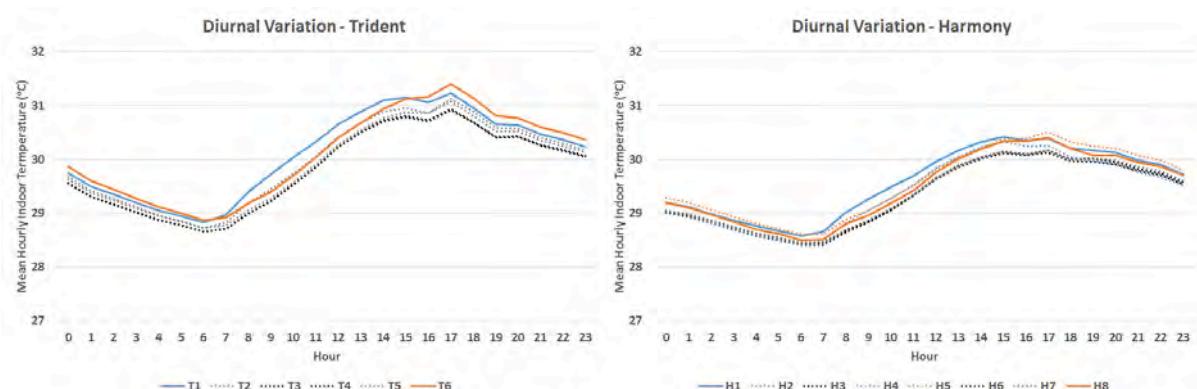


Figure 4. Mean indoor temperature for individual hours for Trident (left) and Harmony (right) using SRY data.

Despite of the lower indoor temperature observed in Harmony units, the diurnal range is lower with the maximum diurnal range ( $1.9^{\circ}\text{C}$ ) found in the west-facing unit (H8). Similar diurnal pattern is observed in Harmony units. As one of the west-facing units (H5) is relatively unobstructed in the afternoon, higher indoor temperature is observed from mid-afternoon to late evening. It suggests that the accumulated heat stored in the unit and retained throughout the night, resulting in potential heat stress during night-time.

## Further Work

The present study compares the level of thermal comfort in two common types of public housing in Hong Kong under typical and near-extreme summer conditions which were represented by TRY and SRY respectively. Numerical modelling was used to obtain information about the PMV values and air temperature in the units of the two dwelling types. It was found that the more recent building type (Harmony) generally provides better thermal comfort in dwellings. It also exhibits smaller increase in thermal discomfort under near-extreme summer conditions in terms of maximum PMV values recorded. Higher PMV values were observed in east- and west-facing units and the west-facing units also showed higher maximum air temperature due to the combined effect of high air temperature in the afternoon and direct sun exposure. Due to the difference in insulation, the Harmony units have a smaller diurnal range of indoor air temperature which provides more stable indoor environmental conditions and better thermal comfort.

Further work will focus on identifying parameters that are potentially influential to thermal comfort and the corresponding effect on energy consumption under different meteorological conditions. Design features will also be identified and findings will be incorporated into future design of public housing which accommodates the majority of population in Hong Kong. Parametric studies will therefore be conducted to examine the sensitivity of different design parameters and determine the extent of how they affect thermal comfort conditions.

## Acknowledgement

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## References

- Cheng, V., Ng, E. (2006). Comfort temperatures for naturally ventilated buildings in Hong Kong. *Architectural Science Review*, 49, pp. 179–182.
- D'Ippoliti, D., Michelozzi, P., Marino, C., de'Donato, F., Menne, B., Katsouyanni, K., Kirchmayer, U., Analitis, A., Medina-Ramón, M., Paldy, A., Atkinson, R., Kovats, S., Bisanti, L., Schneider, A., Lefranc, A., Iñiguez C., Perucci, C.A. (2010). The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environmental Health*, 9, 37.
- Fanger, P.O. (1972). *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw-Hill.
- Hong Kong Observatory (2016). Statistics of Special Weather Events - Number of Very Hot days. Available at: [http://www.hko.gov.hk/cis/statistic/vhotday\\_statistic\\_e.htm](http://www.hko.gov.hk/cis/statistic/vhotday_statistic_e.htm)
- Jentsch, M.F., Eames, M.E., Levermore, G.J. (2015). Generating near-extreme Summer Reference Years for building performance simulation. *Building Services Engineering Research and Technology*, 36, pp. 701–727.
- Kang, J. (2001). Sound propagation in interconnected urban streets: A parametric study. *Environment and Planning B: Planning and Design*, 28(2), pp. 281–294.
- Kaplan, R. (2001). The nature of view from home: Psychological benefits. *Environment and Behaviour*, 33(4), pp. 507–542.

- Lau, K.K.L., Ng, E.Y.Y., Chan, P.W., Ho, J.C. (2017). Near-extreme summer meteorological data set for sub-tropical climates. *Building Services Engineering Research and Technology*, 38(2), pp. 197–208.
- Levermore, G.J., Parkinson, J.B. (2006). Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK. *Building Services Engineering Research and Technology*, 27, pp. 311–325.
- Li, Y., Leung, G., Tang, J., Yang, X., Chao, C., Lin, J., Lu, J., Nielsen, P., Niu, J., Qian, H., Sleigh, A., Su, H.J., Sundell, J., Wong, T., Yuen, P. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. *Indoor Air*, 2007(17), pp. 2–18.
- Roaf, S., Crichton, D., Nicol, F. (2009). *Adapting Buildings and Cities for Climate Change*. Oxford: Architectural Press.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Children thermal comfort in primary schools in Ho Chi Minh City in Vietnam

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**Abstract:** Indoor environmental quality significantly impacts on students' performance and productivity, particularly thermal comfort levels. Currently in Vietnam, very few studies have dealt with the issue and the current trend is to install energy-intensive air-conditioning in primary schools as this is perceived as more comfortable. In this study, the authors investigated the users' perceptions of thermal comfort in three primary schools in Ho Chi Minh City during the mid-season (September 2015) and the hottest season (April 2016). In-situ spot and long-term measurements were recorded. Questionnaires were completed by 2,145 children (from 8 to 11 years-old) and 62 teachers to understand their experiences and the extent of their interaction with the building in 62 naturally ventilated classrooms. The results were analysed by correlating the conditions measured and the comfort mean votes. Throughout this study, children were observed to tolerate higher thermal comfort condition than the recommended values in the standards. Around 7% of the occupied time during academic year presented temperatures over 33°C, in which less than 80% of the children voted acceptable. The results indicated that Vietnamese children had higher thermal comfort tolerance than the comfort levels suggested in the standards. Using air conditioning system all year round was deemed unnecessary.

**Keywords:** thermal comfort, primary school, natural ventilation, indoor environmental quality, children.

### Introduction

The indoor environment significantly impacts on students' performance and productivity (Fisk, 2000, Mendell and Heath, 2005, Teli et al., 2015). Among the factors required to achieve satisfactory indoor environmental quality, thermal comfort can be considered as one of the most important issues, especially in tropical countries (Al horr et al., 2016). After investigating several case studies, Frontczak and Wargocki (2011) stated that the building type, outdoor conditions and the season all have an influence on thermal comfort.

Research on thermal comfort to date has been based on adult comfort and mainly focused on residential buildings and offices. There have been a limited but increasing number of studies about comfortable thermal environment for young children in primary schools. Teli et al. (2015) suggested that UK children's comfort temperature could be 2°C lower than adults', Trebilcock et al. (2017) came to similar conclusions in Chile and de Dear et al. (2015) in Australia. Fabbri (2015) also argued that children are less sensitive to cold condition due to higher metabolism. In summary, a number of field studies showed evidence that children have different thermal comfort requirements than adults and therefore existing international standards, which are based on adults' perception, may not be appropriate for children.

In Vietnam, there has been a few studies about thermal comfort in residential buildings in Da Nang (Nguyen, 2013) and in secondary schools in Ho Chi Minh City (Tran, 2010). Tran (2010) suggested that the neutral comfort temperature for classrooms in secondary schools

was approximately 29.3°C and that the other environmental factors affecting comfort should also be taken into account.

Currently, there is a trend to install air conditioner in primary schools in Ho Chi Minh City due to a perceived need and pressure from parents. One of the case study schools investigated by the authors, which was part of the research for the mid-season (Vi Le et al., 2016), has recently had air condition installed in three classrooms. Parent believed that their children may study better in a cooler environment. However, young children in primary schools may experience thermal environment differently from adults. Therefore, in order to provide a comfortable environment for teaching and learning activities, it is essential to understand the children's perception of the environment in their classrooms.

In this work, the authors have evaluated the thermal environment in naturally ventilated classrooms and the children's perception of comfort in three primary schools in Ho Chi Minh City, Vietnam. Quantitative and qualitative approaches were used in the study. This study is a part of a larger research project developing environmental design standards for primary school in Ho Chi Minh City, Vietnam. The larger study includes other environmental conditions such as daylighting and air quality but these are outside the scope of this article.

### **Case studies**

Three primary schools with similar characteristics all located in central Ho Chi Minh City were investigated. School 1 is in the medium density residential area whilst the others (School 2 and School 3) are in the high density residential area. There are 62 classrooms in total in the three schools with approximately 35 pupils per class on average. The typical room size is 40-50m<sup>2</sup>. The floor-to-ceiling height is 3-3.3m. The walls are made of single/double bricks without thermal insulation. Doors and windows have single glazing and steel frames in School 1 and School 2. In School 3, most of classrooms have wooden louvered windows and a door. There are ceiling fans and artificial lighting in all classrooms. Some classrooms have curtains or blinds. The academic year in Vietnam is from the middle of August to the end of May every year. The school time is 7:00 - 10:00 and 13:00 - 16:00 Monday to Friday. Children wear similar uniform in these schools with the clothing insulation level of 0.55clo on average.

### **Methodology**

Methods used included the collection of environmental data and the deployment of a questionnaire designed by the authors. The sets of data were then correlated to enable the understating of perception of comfort in relation to actual measured data. The periods of data collection included September 2015 (mid-season) and April 2016 (hottest season). In the mid-season, only School 1 was investigated. The typical weather was hot with little rainfall (average daily temperature 29.9°C and relative humidity 73.6%). In the hottest season, the authors conducted the investigation in three primary schools when the weather was significantly hot without rainfall (average daily temperature 31.8°C, relative humidity 68.4%).

### ***Long term recording***

Two modules of a NETATMO environment/weather station were installed in one selected classroom in each school in order to conduct long term in-situ measurement of environmental conditions. The outdoor unit recorded outside air temperature and relative humidity while the internal unit monitored the indoor environmental parameters. The data were recorded every five minutes and continuously recorded from August 2015 to May 2016. The NETATMO system has an accuracy of  $\pm 0.3$  °C for temperature and  $\pm 3\%$  for relative humidity. The long-

term data recorded in School 2 was excluded from this analysis because the classroom where the data was collected was not representative of the norm for the school.

### ***Spot point measurement***

Spot point measurements of temperature and humidity were conducted using an environmental meter inside and outside the classrooms. The accuracy of the meter is  $\pm 3\% \text{rdg} \pm 2^\circ\text{C}$  for temperature and  $\pm 5\%$  for relative humidity. Due to the small room size, temperatures in various points in the classroom were found to be similar. Therefore the temperatures in the middle of class were recorded in controlled intervals in the occupied rooms during the deployment of the questionnaires.

### ***Questionnaire***

Questionnaires were carefully developed by the authors based on an extensive literature review and experience. The questionnaires were carried out at the same time as the spot measurements were made in the occupied classrooms. The target public were children from eight to eleven years old due to their reading skill level required to undertake the survey. The questionnaire contained several questions about indoor environmental quality and was formulated in a way which could help children respond more easily. Perception of the thermal environment was a part of the questionnaire. In mid-season, the children were asked only about their thermal sensation. In the hottest season, the questionnaire included three key questions about thermal sensation (very hot (+3), hot (+2), warm (+1), neutral (0), cool (-1), cold (-2) and very cold (-3)), thermal comfort (yes - no question) and thermal preference (prefer to be cooler, no change, prefer to be warmer).

Teachers also took part in the survey and answered similar questions about thermal sensation, thermal comfort and thermal preference in the mid-season and the hottest season.

### ***Analysis***

This study compared the results from the measurement with the European Standard (EN) 15251 (CEN, 2007) and Vietnamese Building Standard (TCXDVN) 306:2004 (Ministry of Construction, 2004). The Vietnamese Standard TCXD VN 306:2004 (2004) states that the comfort zone for Vietnamese people is  $21.5^\circ\text{C}$ - $29.5^\circ\text{C}$  and that the temperatures in buildings should not be lower than  $19.8^\circ\text{C}$  or higher than  $31.5^\circ\text{C}$ .

The adaptive thermal comfort equation (1) from EN 15251 was adopted in order to evaluate the users' thermal comfort perception because similar equation is not available for the Vietnamese climate. In the equation (1),  $T_{\text{comf}}$  [ $^\circ\text{C}$ ] is the comfort temperature and  $T_{\text{rm}}$  [ $^\circ\text{C}$ ] is the external running mean temperature.

$$T_{\text{comf}} = 0.33 T_{\text{rm}} + 18.8 \quad (1)$$

The European Standard 15251 (2007) specified the Building Categories of indoor environment as shown in Table 1. The Building Category I, II and III are considered for different levels of acceptable environments whilst the Building Category IV is out of expectation and should only be accepted for a limited time of the year (CEN, 2007). The recommended values and the adaptive thermal comfort equation for each Building Category are shown in Table 1.

Table 1 Recommended criteria for thermal comfort in classrooms (CEN, 2007)

	Fixed approach	Adaptive approach
Category I	$23.5^\circ\text{C}$ - $25.5^\circ\text{C}$	$0.33T_{\text{rm}} + 18.8 \pm 2$
Category II	$23^\circ\text{C}$ - $26^\circ\text{C}$	$0.33T_{\text{rm}} + 18.8 \pm 3$
Category III	$22^\circ\text{C}$ - $27^\circ\text{C}$	$0.33T_{\text{rm}} + 18.8 \pm 4$
Category IV	$<22^\circ\text{C}$ or $>27^\circ\text{C}$	

The authors applies the algorithm developed by Montazami et al. (2017), in which the differences between adults' (adopted from EN15251) and children's comfort temperature (calculated from the field study) are compared. The relationship between children's thermal sensation vote and the indoor temperature are considered in order to propose the comfort temperature and the benchmark for overheating calculation in primary schools in Vietnam.

## **Results and discussion**

An analysis of all the data collected in the hottest season showed that throughout the investigation period, the children questionnaire results indicated an overall thermal sensation mean vote of 0.33. Thus the general thermal sensation of the children was comfortably warm in their classrooms when the temperatures ranged from 29.2°C to 36.1°C and the relative humidity ranged from 42.8% to 83.4% (see Table 2).

Table 2 Spot point measurements and the overall thermal sensation mean vote in the three primary schools

	Thermal Sensation Mean Vote	Indoor Air Temperature Range [°C]	Relative Humidity Range [%]
School 1	-0.2	29.2 - 34	49.1 – 83.4
School 2	0.56	31.7 – 35.8	42.8 – 78.5
School 3	0.51	31.1 – 36.1	48.4-79.3

The temperatures measured were higher than 27°C in all investigated classrooms. Therefore they were classified as Building Category IV (CEN, 2007), which is out of the range for good indoor thermal comfort.

If compared with the Vietnamese standards, only seven classrooms presented temperatures below 31.5°C during the investigation period (equivalent to 14% of classrooms) and therefore could be classified as 'acceptable' in terms of thermal comfort conditions, even though they are still out of the desired comfort zone. Only one classroom, which was measured in the morning, presented the temperature of 29.2°C (below 29.5°C) and therefore was within the comfort zone. Generally, the measured conditions did not achieve thermal comfort based on Vietnamese standard.

The results showed that thermal conditions in School 1 differed from the others. Perhaps the location of the buildings caused the differences between the schools but there is not enough evidence to infer this conclusion. Even the best environmental comfort conditions recorded in School 1 were not maintained throughout the day as temperatures would go above the comfort zone from around 8:00am until the end of school time.

### ***School 1 in the mid-season and the hottest season***

The data collected in School 1 were used to compare the mid-season and the hottest season results. The recorded outdoor temperature ranged from 26°C to 35 °C in the mid-season and from 28 °C to 37°C in the hottest season. Compared with the results of the mid-season (Vi Le et al., 2016), the thermal sensation mean vote raised from (-0.43) to (-0.2) when the mean indoor air temperature increased from 29.9°C to 31.8°C and the mean relative humidity decreased from 78.3% to 69% in School 1. The result showed that although the children felt comfortably cool in both seasons, they perceived warmer thermal environment in the hottest season in their classrooms.

### **Children thermal sensation votes**

The relationship between the thermal sensation vote and the offset from the adaptive comfort temperature was plotted and is shown in Figure 1. The relationship between the thermal sensation vote and the indoor temperatures is shown in Figure 2. The data shown includes all the data collected in the mid-season and the hottest season of the year. In general, the indoor air temperatures were higher than the desired comfort temperature as discussed before (based on CEN (2007)).

As shown in Figure 1, the percentage of the children feeling warm-neutral-cold peaked at 86% when the difference between the indoor air temperature and the comfort temperature was about 0.67K. In this condition, 39% of the children voted neutral. The highest percentage (52%) of children feeling neutral occurred when the temperature difference was approximately 3.8K. In this condition, 79.6% of the children voted warm-neutral-cold.

These findings differed from the previous study by Montazami et al. (2017). The children were observed to tolerate higher temperatures than the values recommended for adults in the standards. The percentage of children feeling neutral decreased when the difference between indoor temperature and comfort temperature reduced from 3.8K to 0.67K. However, the percentage of children voting warm-neutral-cold to reach the highest levels (86%).

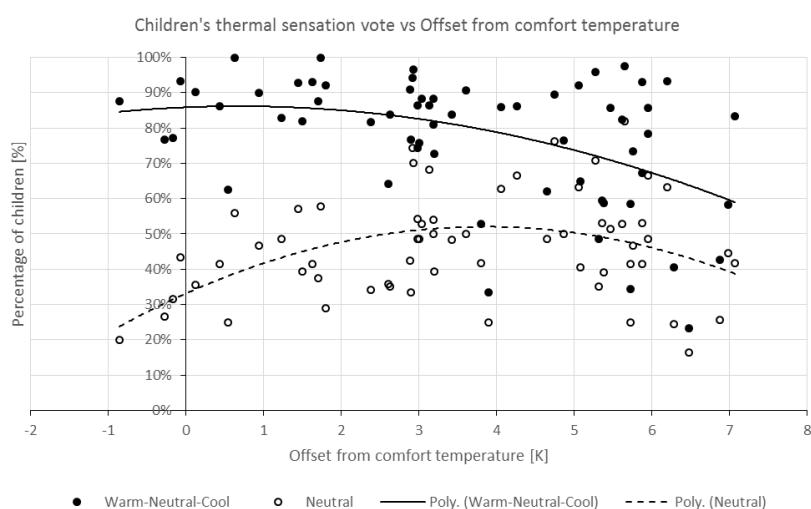


Figure 1 The percentage of children voting Neutral and Warm-Neutral-Cool in relation to the offset from the comfort temperature in the mid-season and the hottest season

In Figure 2 it can be seen that the highest percentage (87.3%) of children voted warm-neutral-cold around 29.9°C while only 41.6% of children voted neutral. In addition, 51.2% of children voted neutral around 32.8°C while 81% of the votes were for warm-neutral-cold. These results suggested that the percentage of children feeling acceptably comfortable (warm-neutral-cold) increased although the number of neutral votes reduced for temperatures below 32.8°C.

In Figure 2, the results showed that 80% of children felt acceptably comfortable at 33°C. Therefore, it can be suggested a maximum temperature of 33°C could be taken as a threshold to evaluate overheating issues in primary schools in Ho Chi Minh City, Vietnam.

The comfort line in Figure 2 shows the percentage of children voting comfortable for the question of 'Do you feel comfortable at the moment?' in the hottest season. The results showed that 87.6% of children felt comfortable at 29.9°C and 77.4% votes for comfort were

at 32.8°C. As seen in Figure 2, the results from the comfort line is likely close to the warm-neutral-cool line at the temperature range of 29.2 °C – 36.1°C. The difference between these two lines was less than 5% at that temperature range. Therefore the thermal sensation vote of warm-neutral-cool could be a reasonable indicator of thermal comfort for children.

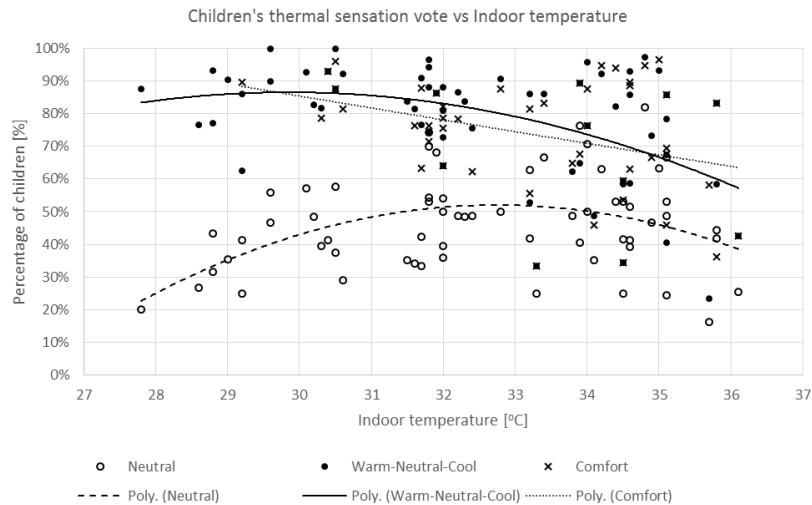


Figure 2 The percentage of children voting Neutral and Warm-Neutral-Cool in relation to classrooms' indoor temperature in the mid-season and the hottest season

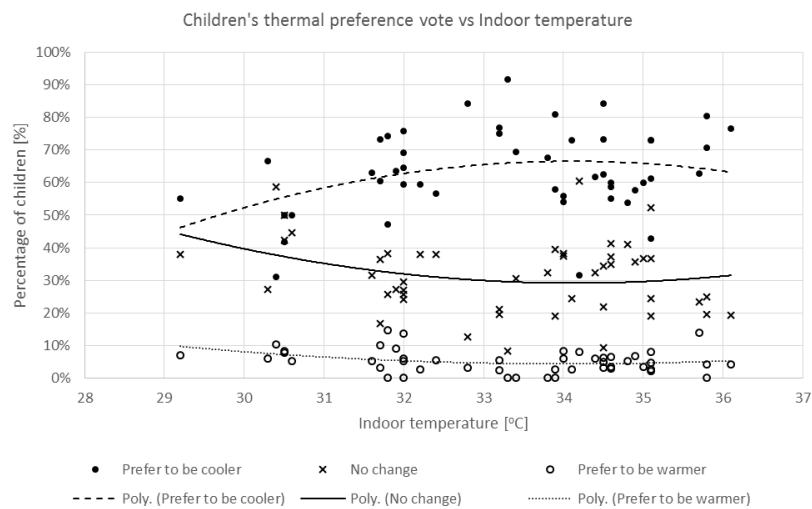


Figure 3 The percentage of children's thermal preferences in relation to classrooms' indoor temperature in the hottest season

As seen in Figure 3, during the hottest season of the year, 63% of children preferred to be cooler and less than 5% of votes preferred to be warmer. When the temperature decreased, the percentage of children wanted 'no change' and 'being warmer' increased and less children preferred to be cooler. Despite the children's responses that they felt comfortable with the current temperature in their classrooms, 38% of the children preferred a cooler thermal environment.

At the temperature of 32.8°C, when the highest percentage of the children voted neutral (Figure 2), the majority of the children (more than 50%) still preferred to be cooler (Figure 3). This suggests that the warm-neutral-cold line is a better indication of thermal comfort. The temperature when most of the children voted warmed-neutral-cool was 29.9°C as shown in Figure 2.

### ***Long term measurement***

CIBSE Guide A (2015) indicated that the threshold temperatures that defines overheating in European schools is 28°C. However, the evidence gathered by this work has shown that children in Ho Chi Minh City have more tolerance of higher temperatures and therefore the authors suggest that overheating should be measured at a higher temperature. Table 3 showed the number of hours in the hottest season when the temperatures were over 33 °C and 34.5 °C, corresponding to 80% and 70% of children voting warm-neutral-cool (Figure 2).

Table 3 Number of hours and percentage of occupied time in unacceptable thermal conditions

Temperature	>33°C	>34.5°C
School 1	52 (2.7%)	0
School 3	134 (7%)	40 (2.1%)

As seen in Table 3, in School 1, in less than 3% of the school time during the academic year the temperatures were over 33°C. As a result, the thermal environment in School 1 was acceptable. This suggests that the use of air conditioning in this school may be deemed unnecessary. In School 3, there was over 120 hours, equivalent to 7% of the occupied time during academic year, when temperatures were over 33°C. Although the building could experience some overheating problem, this indicates that air conditioning is not necessary all year round. It is recommended that air conditioning could be used only around midday when the temperatures go above 33°C. The long-term assessment showed that the thermal conditions in School 1 were better than in School 3. The authors' hypothesis is that the location and the building envelopes may have a large influence on the difference observed but further work is needed to confirm it.

### ***Occupant behaviour and teacher votes***

The teachers gave the long term evaluation of indoor thermal comfort in the mid-season and the hottest season. The teachers' thermal sensation mean vote was 0.77, which was higher than children's. This result implied that the teachers could perceive higher thermal environment than children in the same space. This result was consistent with the findings, indicating that the children have more tolerance to higher temperatures. Similar to the children's preference, the teachers also preferred a cooler thermal environment.

The questionnaire also provided feedback on how the occupants used the building elements and facilities to adjust their thermal environment. The teachers opened doors and turned on the fans and lights during the school time. The children also had opportunities to open/close the curtains and windows when these were close to their desks. The windows were open almost all the time to provide natural ventilation.

### ***Discussion and Conclusions***

This study was undertaken to evaluate the current environmental conditions and users' perception of indoor thermal environment in naturally ventilated classrooms in three primary schools. Ventilation in schools is enhanced on occasion by user controlled ceiling fans as a supplementary cooling method. The investigation was conducted during the mid-season (September 2015) and the hottest season (April 2016).

In general, the thermal environment of the studied primary schools in Ho Chi Minh City in Vietnam in the hottest season did not meet the comfort recommendations in the international and the Vietnamese standards. However, the authors questioned the validity of these standards for children since they are based on adults' responses. The highest percentage of children feeling comfortable was 87.3% when the temperature reached 29.9°C.

Most children felt neutral at 32.8°C. This indicated that Vietnamese children had higher thermal comfort tolerance than the comfort levels suggested in the standards.

The findings also suggested that the benchmark for overheating calculations could increase to 33°C in the hottest season when at least 80% of the children were satisfied with the thermal condition.

The authors suggest that air conditioning all year round, which is current trend in schools in Vietnam, may be unnecessary from a comfort perspective and would lead to unnecessary energy and associated carbon emissions. These findings could help and encourage architects and engineers to design and deliver schools that do not need the aid of air conditioning systems. In the next steps of this study, the authors will explore the influence of design on the thermal environment of primary schools in Vietnam.

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## References

- Al Horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A. & Elsarrag, E. 2016. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5, 1-11.
- Cen 2007. EN 15251:2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels: European Committee for Standardization.
- Cibse 2015. Guide A. *Environmental design*. London: The Chartered Institution of Building Services Engineers.
- De Dear, R., Kim, J., Candido, C. & Deuble, M. 2015. Adaptive thermal comfort in Australian school classrooms. *Building Research & Information*, 43, 383-398.
- Fabbri, K. 2015. *Indoor Thermal Comfort Perception: A Questionnaire Approach Focusing on Children*, Springer.
- Fisk, W. J. 2000. Health and productivity gains from better indoor environments and their relationship with building energy efficiency. *Annual Review of Energy and the Environment*, 25, 537-566.
- Frontczak, M. & Wargocki, P. 2011. Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment*, 46, 922-937.
- Mendell, M. J. & Heath, G. A. 2005. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air*, 15, 27-52.
- Ministry of Construction 2004. Dwelling and public buildings - Parametes for micro-climates in the room. *TCXD VN 306:2004*. Ha Noi, Vietnam: Ministry of Construction.
- Montazami, A., Gaterell, M., Nicol, F., Lumley, M. & Thoua, C. 2017. Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms. *Building and Environment*, 111, 61-71.
- Nguyen, A. T. 2013. *Sustainable housing in Vietnam: Climate responsive design strategies to optimize thermal comfort*. Doctor of Philosophy, University of Liege.
- Teli, D., James, P. a. B. & Jentsch, M. F. 2015. Investigating the principal adaptive comfort relationships for young children. *Building Research and Information*, 43, 371-382.
- Tran, V. T. 2010. *Efficient classroom lighting and its environmental consequences in schools in Ho Chi Minh City, Vietnam*. Doctor of Philosophy, London Metropolitan University.
- Trebilcock, M., Soto-Munoz, J., Yanez, M. & Figueroa-San Martin, R. 2017. The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. *Building and Environment*, 114, 455-469.
- Vi Le, T. H., Gillott, M. C. & Rodrigues, L. T. 2016. The case for hybrid ventilated primary schools in Ho Chi Minh City in Vietnam. *36th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments (PLEA 2016)*. Los Angeles, USA.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Urban External Space in Brazilian Modernist Architecture under the focus of Pedestrian Environmental Comfort

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**Abstract:** This research discusses the environmental performance of urban spaces, focusing the accessibility and comfort of pedestrians, based on the results of two projects: “Evaluation, under the ergonomic emphasis, of modernist buildings built in São Paulo between 1930 and 1964: external areas” and “Pedestrians Thermo-Acoustic Comfort in São Paulo and Other Environmental Variables Influence”. The study presents a diagnosis of the immediate surrounding areas of five iconic modernist buildings in São Paulo: Copan Building, Itália Building, Esther Building, Conjunto Nacional Condominium and Sul-Americano Building (Itaú), which constitute themselves as places of great concentration of activities and subsequently as major attraction sites. They were selected due to their architectonic and historical relevance and the scenario in which they are located: República - one of the first city centre expansions in the beginning of the 20<sup>th</sup> century - and Paulista Avenue - prominent economic centre with huge development since the second half of the 20<sup>th</sup> century. The method reflects the quantitative, qualitative and subjective (perception of pedestrians) evaluation of environmental variables (physical, thermal, lighting, acoustic, ergonomic).

**Keywords:** environmental comfort, performance, pedestrian, perception, modernist buildings

### Introduction

The main goal of this project was to evaluate the performance of urban exterior areas next to some of the Brazilian Modernist Architecture icons produced between 1930 and 1965 in São Paulo, focusing to understand the interrelations of the various urban environmental comfort aspects (thermal, acoustic, lighting, ergonomics, mobility, quality and adequacy of sidewalks, urban design, green areas, etc.). The research is based on the comparative studies of a group of five buildings: Banco Sul Americano (nowadays Itaú Bank), on Paulista avenue, by the architect Rino Levi; Conjunto Nacional, on the same avenue, designed by David Libeskind; Edifício Itália, on Ipiranga Avenue, designed by Franz Heep; Edifício Copan, designed by Oscar Niemeyer; and Edifício Esther, designed by Álvaro Vital Brazil. The main results are the comparative understanding of the characteristics of two strong centralities in São Paulo, República and Paulista Avenue, with very diverse urban aspects and derived from

urban expansion processes at different times, establishing the characterization of pedestrians comfort and discomfort conditions and parameters for local urban quality.

### **Scenario**

The climate scenario of São Paulo is characterized by typically hot and humid summers, with almost daily rains and drizzles, and typically dry winters, with medium cold days and nights. The average temperature is 19°C, with an average minimum temperature of 12°C during the winter and average maximum temperature of 28°C during the summer. Average precipitation goes from 40mm in August (winter) to 240mm in January (summer).

In the second half of the 19<sup>th</sup> century, Brazil became the most important coffee productor and, with this process a new elite was Born in São Paulo, who wanted the city to be like a living space, but the activities that were made in the streets still by slaves and the poorest people did not reflect the image of an important, modern and rich city. So the administration started to implement changes aiming to make São Paulo center look like Paris with boulevards, gardens, plazas and streets inspired in the French city. This style influenced the renovations of the city historical centre and one of the first city centre expansions, República Neighborhood, that showed huge urban development in the first half of the 20<sup>th</sup> century, with narrow streets and "boulevard" avenues, no lateral distancing between the high-rise modernist and "eclectic" buildings that are frontally aligned with the streets.

From 1930, the city took a different urban development path, influenced by the decisive Prestes Maia's Master Plan (called Avenues Plan as well), that inserted in São Paulo a north american model, based mainly on developing car infrastructures. The individual car was chosen as the main transport model and, until the emergence of new initiatives in the 2000's, all the major urban interventions were focused on the car and not on the people, which brought the problematic pedestrian's space that we currently find in São Paulo's streets. This urbanistic vision dominated most of the city expansions during the second half of the 20<sup>th</sup> century, including the quick and striking development of Paulista Avenue as the city's economic and financial centre, with a wide space avenue, marked by generous sidewalks, numerous car lanes and high-rise buildings aparted from each other and from the street by gardens and/or larger sidewalks.

These central built environments show very different urbanistic aspects, but both strongly marked by intense traffic - and consequently intense traffic noise and low air quality due to pollution -, outrageous vegetation removal and excessive use of asphalt and concrete. The urban built density has created urban canyons, marked by intensive noise, wind corridors and drastic changes in the street and buildings insolation conditions. The urban microclimates, built density, surface materials and pollution cause heat accumulation, temperature inversion and heat islands. At some point, we are all pedestrians and subjected to these conditions.

### **Material and Method**

The method used for the assessment was based on the analysis of the relationship between: **quantitative evaluation**, consisting of the measurement and analysis of environmental data, **qualitative assessment**, which consists of understanding the local qualities related to the urban and public spaces design, and **subjective evaluation** through interviews of users' opinions in relation to their space perception, as it is illustrated in Figure 1.



Figure 1. Work Process

The comfort is understood, in this project, as composed by sets of variables: thermal (solar radiation, air temperature and humidity, and wind speed), acoustic (noises sources, characteristics and equivalent level), light variables (luminance, reflections, glare and obfuscation), urban environment (services, facilities, green areas, street quality, air quality, traffic, public furniture, accessibility), sidewalks (floor quality and adequacy, width and obstacles) and subjective personal data (self-declared comfort and perception).

The quantitative data (thermal and acoustic values and pedestrian and vehicles influxes) was produced by in-place measurement, such as influxes counting. The acoustic conditions were obtained through the measurement of noise levels and the calculation of the representative equivalent noise levels using the BISTAFA (2002) method. Similarly, the thermal "landscape" was characterized by the "**TEP - Temperatura Equivalente Percebida**" ("**Temperature of Equivalent Perception**"), an outdoor thermal index specific for São Paulo, proposed by MONTEIRO (2008), that combines in-place measured values of air temperature, speed and humidity, globe temperature, mean radiant temperature, and statistic values of metabolic activity and clothing (adopted as 1,3 Met and 0,6 clo in this project by orientation of the TEP method). The results indicate the expected thermal sensation (see Table 1).

Table 1. Temperature of Equivalent Perception (TEP) - Results (MONTEIRO, 2008)

TEP value	Feel	TEP value	Feel
TEP > 50	Extremely Hot	21,5 < TEP < 25,4	Neutral
42,5 < TEP < 50,0	Very Hot	19,6 < TEP < 21,5	Light Cold
34,9 < TEP < 42,4	Hot	12,0 < TEP < 19,6	Little Cold
27,3 < TEP < 34,9	Little Hot	4,4 < TEP < 12,0	Cold
25,4 < TEP < 27,3	Light Heat	-3,2 < TEP < 4,4	Very Cold
21,5 < TEP < 25,4	Neutral	TEP < -3,2	Extremely Cold

The qualitative analysis (urban environment aspects) embraced the mapping of ergonomic problems, photographic survey, physical conditions survey, sidewalks and plazas' maintenance conditions and urban morphology through in-place evaluation. The second part of the evaluation consisted in assessment cards development. This way, the intention is to evidence issues such as land use, pedestrians and vehicles flows, users' profiles, street connectivity, features of the buildings and space environmental performance, and, in addition, aspects related to safety, accessibility, pedestrian scale, diversity and sustainability.

At last, the subjective assessment was made through 1-minute questionnaire interviews applied to the pedestrians at the same time of the measurements and space evaluation, asking about the comfort and perception in relation to general satisfaction, sun, thermal conditions, light, noise, urban furniture, urban facilities, traffic, safety, vegetation, etc. Figures 2 and 3 shows examples of these quantitative, qualitative and subjective assessment cards.

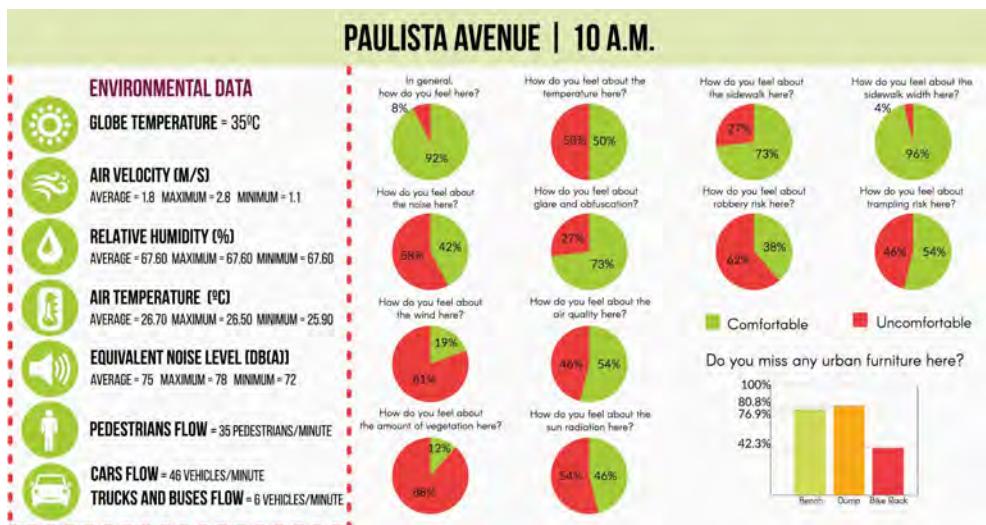


Figure 2. Assessment Card of users perception on Paulista Avenue



Figure 3. Assessment Card of environmental lecture in front of Conjunto Nacional Building

For the complete research, there were made approximately 2500 interviews in 25 measurement events 21 different points during 12 days in all four seasons distributed in 3 years. For this specific study, the sample was composed by approximately 500 interviews in 6 points during 3 days in March, April (autumn) and July (winter), 2015. In the **República Area**: three points in Ipiranga Avenue measured in April: **COPAN Sidewalk** (Figure 4), **Itália Sidewalk** (Figure 5) and **Esther Sidewalk** (Av. Ipiranga sidewalk on the other side of the street, close to the underground entrance and the República Square - Figure 6). In **Paulista Avenue**: also three points were measured: **CN Sidewalk** (Paulista Avenue sidewalk, measured in March and July - Figure 7), **CN Interior** (measured in March, except for the absence of vehicles, it functions as a covered street, open to public and connecting streets, with huge pedestrian influxes, commercial establishments, natural lighting and even wind -

Figure 8) and **Itaú Sidewalk** (Sul-American Building - Itaú - sidewalk in Paulista Avenue - Figure 9).



Figure 4, 5, 6, 7, 8 and 9 (from left to right). Photographs from the measurement points

## Results

The measurement days in March and April showed high temperatures, clean sky, and heavy solar radiation, while in July it presented clean sky, medium temperatures and medium solar incidence. The points have the following **sidewalks widths**: COPAN Sidewalk - 20,4m (22,3 yd), Itália Sidewalk - 13,2m (14,4 yd), Esther Sidewalk - 7,8m (8,5 yd), CN Sidewalk - 9,3m (10,2 yd), CN Interior - 7,0m (7,7 yd) and Itaú Sidewalk - 12,2m (13,3 yd). The diagnosis registered heavy **pedestrian traffic** in all points: around 1000 to 2000 pedestrians/hour in COPAN Sidewalk and Esther Sidewalk, and up to 3680 pedestrians/hour in Itália Sidewalk. In CN Interior it was around 800 to 2200 pedestrians/hour, in CN Sidewalk it went from 1140 to 3380 pedestrians/hour, smaller than Itaú Sidewalk, with 1600 up to 4240 pedestrians/hour. Also **vehicular traffic** is heavy: in Repúbliga points around 1000 to 3500 vehicles/hour, with 5% to 13% of heavy vehicles (ex. buses), while in Paulista Ave. (except CN Interior) there were around 1700 to 3800 vehicles/hour with 3,3% to 8,1% of heavy vehicles.

Intense **Equivalent Noise Level**: almost always above 70 dB(A) in all points (except for Itaú Sidewalk), in Repúbliga points it went from 69 dB(A) to 73 dB(A) and in Paulista Avenue from 67 dB(A) to 79 dB(A). COPAN sidewalk presented the lowest noise levels among the Repúbliga points during off-peak hours, which would be due to lower traffic intensity and bigger distance between the sidewalk and the street lanes, separated by parking lanes and trees. Surprisingly, the self-declared acoustic comfort was the lowest in COPAN Sidewalk (around 20%). This might be related to the users' different expectations to these different spaces: Itália sidewalk is a narrow unshaded corner between two busy avenues while COPAN sidewalk is a wide path shaded by trees with parking areas and cafes, which means that the first point is less satisfactory and seen as a "pass-by" space while the second one is a more comfortable area configured as a place to stay, not only passing by. This different expectation reduces the tolerance of pedestrians to the noise and other adverse conditions.

In Paulista avenue, we also found intense equivalent noise levels above 70 dB(A) during all day on CN Sidewalk and CN Interior while the Itaú Sidewalk levels were almost constant and under the mark of 70 dB(A). Although, even when the CN Interior point showed noise levels around 5 dB(A) higher than the exterior Itaú Sidewalk point, the percentages of self-declared acoustic comfort were significantly higher (up to 30% higher) than the exterior points. Exterior noises were originated mainly from traffic (vehicles, sirens and horns), nearby construction sites, and musicians presentations in the streets (which was pointed as a pleasant sound by pedestrians but sometimes as a disturbing noise by people

that work in the neighboring buildings). Interior noises come mostly from the exterior noise sources and from internal speech noise due to the numerous people staying and passing by.

In Itália Sidewalk and Esther Sidewalk points, it was measured intense ***thermal heat conditions*** with high TEP values due to high solar incidence and high air temperatures. At the same times, COPAN sidewalk showed the lowest TEP values due to the shading of numerous big trees. Itália Sidewalk showed significantly higher TEP values (around 10 to 13 points of difference) related to the stronger incidence of solar radiation. Also thermal comfort was low in these points (around 60%), but unexpectedly higher in Itália Sidewalk, especially during the afternoon when TEP values were medium. Even though, general comfort was better in COPAN Sidewalk (around 90%) during all day, since it is greener, more shaded and more inviting.

The points in Paulista Avenue showed in March medium to high TEP values, related to high values of solar radiation incidence and medium air temperatures. There was a significant difference between measurements taken in March and July, this last one with TEP values 5 to 10 points below the first, marking a colder perception of the thermal landscape. In July, during the winter, TEP values were lower due to lower air temperatures and higher wind speeds. The difference was not bigger because July is a typical sunny winter month in São Paulo, presenting mostly clean sky and medium insolation conditions.

Between the two Paulista Avenue external measurement points, both of them with exposed areas and shaded areas under the buildings marquises, Sulamericano Building (Itaú Bank) has a sidewalk almost completely shaded: rich in trees shading, bringing more comfortable spaces to the pedestrians in hot and sunny weathers. We could realize that in a cold winter day, people would prefer exposed sunny spaces, but during hot sunny days, the pedestrians show preference mostly for shaded spaces, and, besides that, the shading occasioned by trees is perceived in a different way than the one formed by the buildings.

That way, Conjunto Nacional showed significantly higher TEP values (around 5 points bigger than Itaú Sidewalk) because of its higher exposure to sun radiation, but showed a bigger self-declared thermal comfort rate during winter measurement due to the expectations and adaptations of the pedestrians to the season climate, while during summer measurements, Sulamericano Building (Itaú Bank) showed bigger thermal comfort. The inner point (CN Interior), at last, showed medium TEP values, with high air temperatures (lower but close to the external air temperatures) but without solar radiation. CN Interior point has also shown the highest self-declared thermal comfort rates during summer measurements due to the more convenient and shaded space, but it was never higher than 80%.

Generally, there is a great ***satisfaction with the sidewalks*** (always above 70% and up to 95%). The lowest satisfaction is in CN Sidewalk, which can be related to the excess of obstacles. In all points, pedestrians declared a great satisfaction (around 90%) with the ***sidewalks widths***, but lower satisfaction with their conditions due to the low quality and inadequacy of floors and pavements and presence of obstacles, especially bumps. All external points present lots of obstacles in pedestrians' routes, such as light and electric posts, public telephones, bus stops, newspaper stores, street vendors, musicians, trees, etc. Even the CN Interior point showed a great number of obstacles (benches, garbage cans, exhibition posts, snack bars, phones, etc). Although the items in the sidewalks configure obstacles to pedestrian traffic, much of them don't disturb the quality of the street and neither the perception of most of the people. Besides, in these areas, the sidewalk have a really great and adequate width, which can minimize the effects of these obstacles.

**Natural illumination** could be a point of discomfort since urban canyons, like this areas, can generate badly lit open spaces even during the day. Nevertheless, in all points, the illumination conditions (quality and amount of light) were well evaluated during the daytime. Although, glare and obfuscation caused by sun reflections in glass building facades and cars were pointed by a significant amount of interviewed pedestrians, mainly on Paulista Avenue, where a great number of buildings have glazed surfaces, while in República Area the majority of the buildings, have opaque (concrete, masonry, etc.) facades with glass openings but the whole glazed facades. Other relevant complaints from the pedestrians were about security (especially during night time), strong winds (even in CN Interior point, where there are intense air movements between openings), excessive noise (even in CN Interior point as well), lack of green areas and excessive sun radiation. General comfort has shown to be the best in CN Interior point (around 95%), since the space is more inviting and offers better conditions for staying (this is the only point that has benches) and shading. Nevertheless, even in this point, the general comfort with the environment was much higher than both separated acoustic and thermal comfort. Therefore, in these points, we can say that the general comfort relies mostly on people's expectations on what to find in these places.

## Discussion

From these analysis, it was concluded that a street in São Paulo, to be considered comfortable by the majority of the pedestrians shall provide shading and protection against overexposure to the sun, as well as solutions to create both expose open-to-sky areas and shaded spaces. It shall permit air movement for sanitary conditions and adequate removal of pollution and heat. The urban design must be thought not to cause the growth of urban canyons.

These series of surveys evidenced that, in São Paulo, the most incident factor on the pedestrian comfort is the thermal comfort, and the globe temperature is the best and most reliable value to understand it. Solar radiation is the most incisive subfactor over the user's general comfort: during the summer the pedestrians tend to look for shaded spaces while during the winter they have a bigger tolerance and desire for open-to-sky sunny spaces.

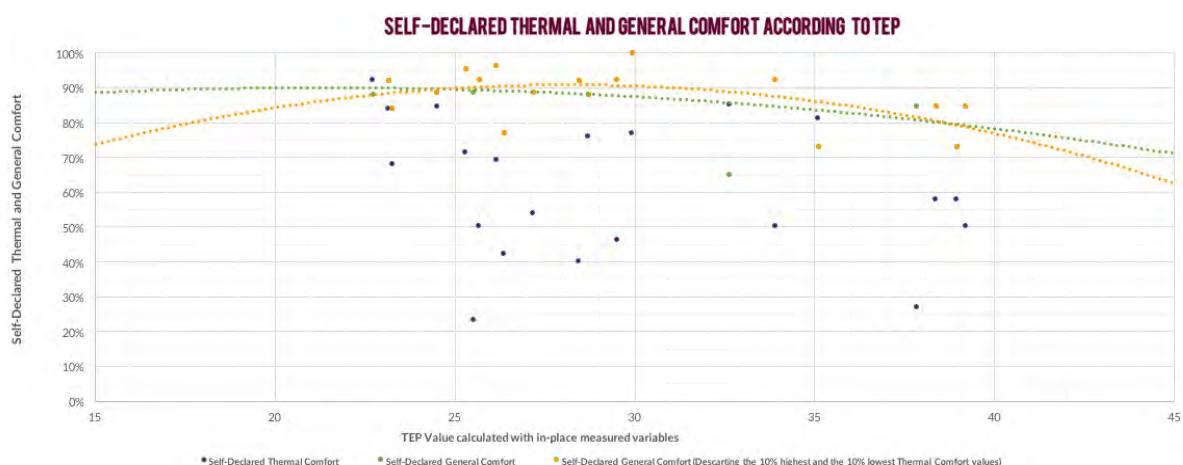


Figure 10. Thermal Comfort and General Comfort x TEP - Temperature of Equivalent Perception

When in thermal discomfort, the pedestrians show lower tolerance to the other environmental variables and tend to declare general discomfort with the environment. As

shown in Figure 10, General Comfort is higher when TEP results are in neutral and light heat conditions, and excluding the statistical extremes (10% highest and 10% lowest values of thermal comfort), we find a General Comfort higher than 90% when  $26 < \text{TEP} < 31$ . These values are similar to the complete research, which showed thermal and general comfort rates above 80% for  $24 < \text{TEP} < 32$ , and thermal comfort rate above 90% for  $26 < \text{TEP} < 30$ . When in thermal comfort, they pay a bigger attention to the other variables. The satisfaction with sidewalk width and acoustic comfort come both next as most relevant factors.

For acoustic comfort it is not only the equivalent noise level that matter, but also the noise source and the expectations with the street size and use that can change drastically the user's tolerance to the noise. In a large influx avenue it is expected to have high levels of traffic noise, so the tolerance to this noise source is higher than in less busy streets. This leads to high general comfort in avenues even when the noise levels are high and acoustic comfort is low, especially when thermal comfort is very high at the same time. Other noise sources, other than the traffic noise, can cause bigger disturbances even when noise levels are lower than traffic, such as horns, buses, sirens, construction sites, etc. So, in busy avenues points, where the equivalent noise levels went up to 79 dB(A) and were due mainly from traffic, it was still possible to find more than 80% of general comfort during most of the time. And interestingly, when it was registered the "optimum" thermal conditions - when thermal comfort was at its highest rates with  $23 < \text{TEP} < 30$  - acoustic comfort is higher.

The sidewalk must be adequate to the street total width, buildings sizes and pedestrians flows, presenting a wide "walking lane" free of obstacles or flooring issues. When in satisfaction with the sidewalk width, pedestrians shall perceive the flooring (quality and adequacy: type of pavement, absence/presence of bumps, accessibility) and obstacles. It is also important to understand the uses of the space and the different kinds of items that can be placed in the streets with no loss of quality of the public space. Green infrastructure is always well perceived and evaluated, even if it brings negative consequences to the pedestrian traffic in the sidewalk, the presence of musicians and art and other street vendors was not a source of complaints either, as well as bus stops (since it is an important need). It's important to observe that the diversity of buildings, people and activities that happen in a street is a subjective factor that can be decisive to the user's choice for one space over another, besides of the environmental factors, such as thermal and acoustic comfort. In São Paulo people like to walk on Paulista Avenue even with the high noise level because of the art performances that happen in this space, for example. The sum of qualitative and quantitative aspects is important to understand and to design better spaces for pedestrians in big cities like São Paulo.

## References

- Bistafa, S. R. (2002). *Acústica aplicada ao controle de ruído*. São Paulo: Edgar Blücher.
- Cambiaghi, Silvana S. (2004). *Desenho Universal: Métodos e Técnicas de Ensino na Graduação de Arquitetos e Urbanistas*. Master. Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo.
- Corbella; Yannas (2009). *Em Busca de Uma Arquitetura Sustentável Para os Trópicos*. Rio de Janeiro: Revan.
- Monteiro, Leonardo M. (2008). *Modelos Preditivos de Conforto Térmico: Quantificação de relações entre variáveis microclimáticas e de sensação térmica para avaliação e projeto de espaços abertos*. PhD. Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo.
- Schmid, Aloísio L. (2005). *A ideia de conforto: reflexões sobre o ambiente construído*. Curitiba: Pacto Ambiental.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Conflict for Comfort: Examination of office workers' ratings of Indoor Environmental Quality and conflict over comfort

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**Abstract:** Offices are important to wellbeing, health and productivity of occupants. Dissatisfaction with environmental conditions of offices is widespread. When people sharing offices have differing comfort preferences it can lead to conflict between colleagues. This work explores if environmental comfort conflict affects users' ratings of office Indoor Environmental Quality (IEQ). This study uses a Building Use Studies (BUS) questionnaire, with additional questions on conflict, to assess the quality of offices within 8 different buildings. Ninety-seven participants' responses have been included in the analysis. The results show 51% have had conflict with a colleague in the year 2016, regarding one or more elements of office comfort. The prevalence of conflict was: heating 43%, cooling 40%, ventilation 37%, noise 36%, light 27%. Student's t-tests between those who had conflict compared to those who did not, reveal those who have experienced conflict rate their office's quality statistically significantly poorer, rating them up to 20% worse. These results suggest that environmental comfort conflict and office occupants' ratings of IEQ are related. This work concludes with a discussion of potential causes that could be explored in further work.

**Keywords:** Indoor Environmental Quality, Building Use Studies, Interpersonal Conflict, Colleagues, Comfort

### Introduction

The quality of offices affect workers' health and productivity (Fisk et al. 2011), therefore, the quality of offices is important at the individual, organisational and societal levels. Open plan offices are becoming the predominate office layout, workers, however, often have diverging ideals for their environment (Frontczak and Wargocki 2011). The ability to control the indoor environment has been shown to improve worker satisfaction with the Indoor Environmental Quality (IEQ), however, in shared spaces, it is unlikely to satisfy all occupants. Conflict over office temperature has been found to be a leading cause of conflict between employees in polls (Behan 2015, CareerBuilder 2015), though built environment and organisational psychology research have not investigated shared office conditions as a trigger for conflict.

A report by Consulting Psychologists Press (2008: 5, 27) states that 80% of UK workers have experienced some conflict, spending on average 1.8hrs per week dealing with workplace conflict; 57% state that conflict left them with negative feelings. Further confirmed by a report by the Chartered Institute of Personnel and Development (CIPD 2008), almost half of human resources professionals frequently manage conflict, spending 3.4hrs each week managing conflict. Interpersonal conflict can be demotivating, and lead to further negative outcomes, such as personal insults, bullying, illness and absences. The effect of conflict can have a large

cost to organisations, for example in 2008 in the United States had 2.8hrs of conflict per week per employee, equating to \$359 billion in paid hours (Consulting Psychologists Press Inc. 2008: 2), without considering the cost of other effects.

Rahim (1992: 371–2) defines conflict as an "interactive process manifested in incompatibility, disagreement, or difference within or between social entities", these can be organisations, groups or individuals. Rahim states that conflict can be caused by a shortage of a desirable resource, imposed engagement, difference in behavioural preferences, having different attitudes, values, skills and goals. Moderate conflict is viewed as healthy and a normal part of human interaction. Conflict can have a positive or negative effect, depending on the type of conflict. Individual conflict are more likely to be negative, compared to task-related conflict, task-based conflict can bring alternative viewpoints and creativity to projects. Hence, conflict over environmental conditions is likely to be negative for individuals, and consequently organisations.

Indoor Environmental Quality (IEQ) is the product of the interactions of external conditions, the building, the building services, the people and activities within them. Models of IEQ are based on understanding that occupants have different needs and preferences for environment; for example, thermal comfort model of Predicted Percentage Dissatisfied (PPD), goes as far as estimating disapproval of the temperature. Differences in comfort requirements could also be partially through differing sensitivity to environmental stimuli (Ursin 2014). This approach leads to the current situation where conflict over office conditions is often viewed as a product of differing comfort preferences.

Most triggers for conflict studied are organisational or psychological; physical environment factors have largely been ignored. These investigations of the physical environment effect on conflict have largely focused on privacy and density of occupants in open plan offices (Ashkanasy et al. 2014, Ayoko and J. Härtel 2003). Ayoko and Härtel (2003: 388, 408) conclude that territorial aspects of office occupancy should be considered to reduce workplace conflict, as physical and psychological control over space gives employees self-affirmation; however, this territoriality may also be applicable to environmental control.

Danielsson et al (2015) has identified a relationship with office noise and conflict in a large sample from Swedish Longitudinal Occupational Survey of Health. Though a strong relation was found with office type, Danielson et al (2015: 168) concludes that office noise is a mediator of office type on conflict, the study investigates overall conflict within offices and does not break down the perceived source of conflict.

The recall of infrequent and none specific events of indoor air quality surveys has been criticised by Hedge (1996) as a weakness, potentially explaining the lack of association of self-reported sick buildings syndrome symptoms and air quality in previous studies. Likewise, the unprompted recall of conflict regarding environmental conditions with colleagues, due to its infrequent and stressful nature may, when completing IEQ surveys introduce recall bias in these results.

Conflict is common in workplaces and offices, environmental comfort is a trigger for conflict. The link between Indoor Environmental Quality and environmental comfort conflict is not established. Understanding the mechanisms linking conflict and IEQ could lead to improved office quality and ensure the validity of IEQ surveys.

## Methods

This work intends to inform future studies design, by identifying key relationships between environmental comfort conflict and IEQ. This work aims to assess if there is a relationship between office conditions (assessed with a standard built environment research questionnaire) and the experience of conflict over environmental conditions.

A cross-sectional field study has been chosen to assess the relationship between conflict and IEQ. Due to the individual nature and infrequency of an interpersonal conflict, a questionnaire using recall of conflict has been used.

Dykes and Baird (2013) conclude that Building Use Studies (BUS) and Centre for the Built Environment (CBE) surveys are the most developed questionnaire-based methods for assessing IEQ. The BUS method was selected for this study as this method has been used extensively in the UK previously. A full BUS licence was obtained from Usable Building Trust.

The BUS questionnaire asks about four elements of IEQ (i.e. thermal comfort, air quality, light and noise). These elements are scored with subscales, which are combined for the results. Scores on thermal comfort and air quality are broken into summer and winter seasons. The light and noise are assessed without subdividing into seasons.

A scale for environmental comfort conflict was created, due to lack of previous suitable environmental conflict standard questionnaires. Environmental conflict was assessed with a question rating the most severe disagreement with a colleague(s), in the last year, which is rated from "Not Stressful" to "Very Stressful" (Figure 1). The conflict question is in the sections of: heating, cooling, ventilation, light and noise. Prompts for elements of office environmental controls which may cause disagreement were included, as shown in Figure 1.

Stress has been used as a scale to rate the 'intensity' of the conflict, as it is a concept widely understood by the public without further elaboration within the survey as conflict is often stated as a source of stress (Kinman and Jones 2005).

Disagreement with colleagues											
Could you rate the most severe disagreement with a colleague(s) in the last year regarding environmental conditions, in this office only											
Please tick each scale											
Heating	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Conflict	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Cooling	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Ventilation	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Lighting	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Noise	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
Conflict	No	<input type="checkbox"/>	Not Stressful	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	Very stressful
<i>Please consider:</i>											
<i>Ceiling/desk lights</i>											
<i>Blinds/curtains</i>											
<i>Windows</i>											
<i>Air conditioning</i>											
<i>Odours</i>											
<i>Ceiling/desk fans</i>											
<i>Radiators</i>											
<i>Heated/cooled air</i>											
<i>Dehumidifiers/humidifiers</i>											
<i>Music</i>											
<i>Office equipment noise</i>											
<i>Noise from the building</i>											

Figure 1. Extract from questionnaire, showing conflict questions.

The survey was structured with the BUS questionnaire before the conflict questions. The conflict questions were separated from the BUS questionnaire, with the intention of not influencing the BUS results. It is assumed that participants did not return to the previous section of the questionnaire and adjust IEQ responses following questions on conflict. However, due to this separation, all factors of conflict and IEQ will need to be cross-correlated.

### ***Calculation of environmental dissatisfaction***

Dissatisfaction with the office environment was calculated from the BUS questionnaire. This was achieved by using the absolute distance from the ideal score on each scale. This is then averaged with other measures in the category, the average was used to reduce the influence of missing answers, compared to summing the scores.

For example: 'Too Hot' to 'Too Cold' scale has an ideal score in the centre of the scale, the central score would yield a score of 0, the extremes on the 1-7 scale, would yield a dissatisfaction of 3. The 'Uncomfortable' to 'Comfortable' scale would score 'Uncomfortable' at 6 and 'Comfortable' at 0.

This non-standard analysis of BUS questionnaire, was used to examine individual participants rather than at a building level, to account for the pilot study's small sample size. This use of the scales assumes that all elements of each scale are of an equal importance to dissatisfaction with the environment within each IEQ element.

Disagreement is dichotomised into those who have not had a conflict (score = 0) and those who had a conflict (scores between 1-7), this data is not transformed for the analysis. The results were analysed using R Studio.

### ***Study Buildings***

This study is constrained to office staff in Coventry, United Kingdom. Eight buildings were chosen from the Coventry University city centre campus, to allow for similar climate and external conditions. The buildings chosen were a mix of ages, construction types and mix of converted and purpose built structures. The buildings are heated and controlled centrally by the university's building management system. Air conditioning and mechanical cooling is only available in a few rooms and not standard throughout the campus. Ventilation varies by building, but is predominantly naturally ventilated through openable windows. Lighting is predominately provided by fluorescent tube luminaires, with timed motion sensor switches.

The use of a variety of different buildings and types is deliberate, in the expectation of gathering a wider range of environmental ratings.

### ***Study Participants***

Participants were from the target university buildings. This allowed similar types of organisational pressures, with a variety of work roles. No exclusion of participants was used during the distribution of surveys. Participants were recruited by the researchers approaching staff and briefly explaining the project and requesting participation. Completed surveys were returned through the internal post.

### ***Ethics***

Ethical approval was granted by the university's ethics board. Participation was voluntary and confidential. An informed consent form was included within the survey.

### ***Results***

476 printed surveys were distributed to university staff and research students, among 8 buildings on the campus. Surveys were completed between November 2016 and January 2017. There was a response rate of twenty six percent, with 124 surveys returned. The returned surveys comprise of office staff ( $n= 73$ ), PhD students ( $n = 20$ ), lecturers ( $n = 13$ ), librarians ( $n = 11$ ) and technicians ( $n = 5$ ).

The following responses were excluded from analysis: incomplete consent (2), PhD students (20) and respondents who do not share an office (8). This analysis used 96 responses. The demographic of these participants is shown in table 1.

Table 1. Demographic of participants included in analysis.

	<b>Male</b>	<b>Female</b>
<b>Age under 30</b>	n = 3	n = 23
<b>Age 30 and over</b>	n = 23	n = 44

In the last year, 51.6% of respondents had at least one conflict with a colleague over environmental conditions in the office. Conflict over heating was the most common aspect of IEQ to cause disagreement in the sample, lighting was the least. Prevalence of conflict by IEQ element is shown in table 2, the mean 'stressfulness' is generally rated low. There is a linear relationship between prevalence of a conflict and its average 'stressfulness', with the more common conflicts rated on average more stressful.

Table 2. Percentage of respondents reporting conflict in the last year and mean stress stressfulness, by indoor environmental quality aspect

	<b>Percentage Reporting Conflict</b>	<b>Mean Stressfulness Reported</b>
<b>Conflict Heating</b>	42.6 %	4.0
<b>Conflict Cooling</b>	40.4 %	3.8
<b>Conflict Ventilation</b>	37.2 %	3.7
<b>Conflict Light</b>	27.2 %	2.7
<b>Conflict Noise</b>	35.9 %	3.6

Conflict and dissatisfaction with IEQ distributions were within a  $\pm 2$  skewness and  $\pm 7$  kurtosis, therefore a parametric t-test was used to assess differences between age and gender of conflict with colleagues and dissatisfaction with the environment; no significant differences were found.

The mean dissatisfaction of those who had conflict is greater for all areas of IEQ, compared to those who did not report conflict. Student's t-tests was used to assess the difference in dissatisfaction of IEQ between those who have had conflict, compared to those who have not. The difference between means has been converted into percentages of total, shown in table 3, reveal those who have experienced conflict rate their offices quality significantly poorer compared to those who have not experienced conflict, in all areas of IEQ. Six relationships between conflict and IEQ remain statistically significant after correcting for multiple comparisons with a Holm adjustment.

Those who had conflict over heating rate both the summer air and winter air statistically worse (Holm adjusted values,  $p = .029$  and  $p = .013$ , respectively), on average about 15% poorer. Those who had conflict over cooling have greater dissatisfaction over winter air (Holm adjusted  $p = .001$ ), rating it on average 18.5% poorer.

Those that had conflict over office noise also rated noise, on average 17.3% worse, compared to those who did not have conflict (Holm adjusted  $p = .006$ ).

Summer temperature dissatisfaction had significant differences of means of experience in lighting and noise conflict (Holm adjusted values,  $p = .002$  and  $p = .026$ , respectively), with

differences of 19.9% and 17.5% respectively. The connection between light and noise conflict and summer temperature requires further exploration, however within open comment sections of the BUS survey some participants noted having to choose between natural ventilation by opening windows and limiting external noise by closing windows.

Table 3. Difference between means of dissatisfaction of those who had environmental comfort conflict compared to those who did not, with p-value of statistical significance highlighted.

	Summer Temperature Dissatisfaction		Winter Temperature Dissatisfaction		Summer Air Dissatisfaction		Winter Air Dissatisfaction		Light Dissatisfaction		Noise Dissatisfaction	
<b>Conflict over Heating</b>	NoCon	1.84	NoCon	1.50	NoCon	1.74	NoCon	2.24	NoCon	2.35	NoCon	1.96
	Con	2.18	Con	1.80	Con	2.44	Con	2.99	Con	2.82	Con	2.29
	Diff	8.4%	Diff	7.5%	Diff	14.7%	Diff	15.8%	Diff	9.9%	Diff	9.0%
	P.val	.187	P.val	.083	P.val	<b>.001*†</b>	P.val	<b>.000*†</b>	P.val	.094	P.val	.170
<b>Conflict over Cooling</b>	NoCon	1.86	NoCon	1.85	NoCon	1.49	NoCon	1.69	NoCon	2.34	NoCon	2.38
	Con	2.35	Con	2.18	Con	1.84	Con	2.58	Con	2.82	Con	2.65
	Diff	12.2%	Diff	8.0%	Diff	7.3%	Diff	18.5%	Diff	9.8%	Diff	6.9%
	P.val	.039*	P.val	.206	P.val	.050*	P.val	<b>.000*†</b>	P.val	.051	P.val	.267
<b>Conflict over Ventilation</b>	NoCon	2.27	NoCon	1.96	NoCon	1.79	NoCon	1.53	NoCon	1.82	NoCon	2.33
	Con	2.80	Con	2.23	Con	2.30	Con	1.81	Con	2.54	Con	2.73
	Diff	13.2%	Diff	6.6%	Diff	10.6%	Diff	5.9%	Diff	15.1%	Diff	10.2%
	P.val	.018*	P.val	.277	P.val	.050*	P.val	.131	P.val	.002*	P.val	.053
<b>Conflict over Lighting</b>	NoCon	2.18	NoCon	2.30	NoCon	1.87	NoCon	1.80	NoCon	1.48	NoCon	1.82
	Con	2.98	Con	2.79	Con	2.40	Con	2.40	Con	2.01	Con	2.36
	Diff	19.9%	Diff	12.2%	Diff	11.0%	Diff	12.6%	Diff	11.1%	Diff	13.9%
	P.val	<b>.000*†</b>	P.val	.031*	P.val	.028*	P.val	.043*	P.val	.014*	P.val	.013*
<b>Conflict over Noise</b>	NoCon	1.72	NoCon	2.26	NoCon	2.27	NoCon	1.93	NoCon	1.92	NoCon	1.38
	Con	2.42	Con	2.90	Con	2.88	Con	2.46	Con	2.06	Con	2.05
	Diff	17.5%	Diff	15.9%	Diff	12.8%	Diff	11.1%	Diff	2.9%	Diff	17.3%
	P.val	<b>.001*†</b>	P.val	.002*	P.val	.008*	P.val	.059	P.val	.607	P.val	<b>.000*†</b>

NoCon = Mean dissatisfaction of those reporting no conflict. Con = Mean dissatisfaction of those reporting conflict. Diff = Difference between means, as a percentage of maximum potential dissatisfaction.

P.val = Statistical significance from Student's t-test, between those who had conflict compared to those who did not. \* = Denotes P.value is < .05 . † = Denotes P.value is < .05 following Holm adjustment

Correlation between stressfulness of conflict and dissatisfaction with IEQ has been assessed. This removed all participants who did not experience conflict, this reduced the sample sizes for correlation. Correlation shows some relationships, although, none remain statistically significant after correcting for multiple comparisons with a Holm adjustment.

## Discussion

This study focuses on four potential hypotheses linking environmental comfort conflict with IEQ ratings, the results from this study are interpreted through these explanations.

### 1) Sensitivity

The strong difference in means between dissatisfaction with light across all types of conflict, could potentially mean that people who engage in conflict are more sensitive to environmental stimuli than their colleagues (Ursin 2014). This sensitivity could, therefore, manifest in a desire to adjust the office environment more frequently or to greater extremes than their colleagues potentially leading to conflict.

## **2) Territoriality**

Ayoko and Härtel's (2003) work on territorially could be expanded to encompass control of environmental conditions. Therefore, the use of environmental controls, against the wishes of colleagues, could be used to assert ownership and control over a space, therefore used for psychological wellbeing rather than physical comfort. This may be detectable between offices that have 'hot-desks' and clear desk policies, compared to traditional offices which have more mechanisms for personalisation, through differing rates of environmental comfort conflict. Post hoc reasoning could lead to the poorer ratings of IEQ following environmental conflict for territorial purposes.

## **3) Poor indoor environmental quality causing conflict**

The difference between ratings of IEQ by experience of conflict could be taken at face value, potentially poor IEQ could increase conflict between colleagues, through varying environmental conditions and lack of precise environmental controls. This is potentially supported by Danielsson *et al* (2015) work, showing a link between all conflict and office noise disruptions.

## **4) Recall bias of conflict causing poor indoor environmental quality ratings**

Office quality surveys which use recall could be affected by recall bias (Hedge 1996). Conflict being stressful and infrequent may lead to stronger memories of the indoor quality, especially for those who perceive it poor enough to argue over. The correlations between stressfulness of conflict and environmental dissatisfaction, although non-significant, support recall bias hypothesis if IEQ is viewed as dependent upon the stressfulness of conflict.

## **Conclusion**

This work has examined environmental comfort conflict along with office conditions assessed with the BUS questionnaire. It has found that conflict over office conditions is common with over half sampled reported conflict over one or more aspects of office comfort in the last year, though, the average 'stressfulness' of these conflicts is low.

This work shows that staff which reported conflict on average rated their office IQE worse. No significant correlation between 'stressfulness' of conflict and environmental dissatisfaction have been observed, though this may be due to the small sample size. The strength of the difference in means and significance of dissatisfaction comparing those who experienced conflict to those who have not, lead us to conclude that conflict over office environmental conditions is related to workers' ratings of office IEQ. However, these results do show significant differences in means in conflict experience that are not logically connected, but other studies show that IEQ factors can be interrelated. However, neither the cause nor direction of influence is resolved from this work.

The association between office workers who had conflict office rated their offices worse, compared to those who did not and fit with common sense expectations. Additionally, reported conflict is of a similar frequency compared to polls (Behan 2015, CareerBuilder 2015), and supports Danielsson *et al* (2015) link between noise and conflict, gives further weight to this exploratory survey.

This study assumes the cross analysis of environmental conflict with IEQ are both linear in scale. A limitation of this project is the sample size, the small sample has prevented comparing workers between buildings and rooms, leading to the assessment of the cohort together. Further study with a larger population size would be welcomed. Also with a large-

scale testing BUS results could be calculated at the building level as intended. This study lacks the testing of hypotheses of the potential mechanism linking environmental comfort conflict to IEQ ratings. However, it does demonstrate that environmental comfort conflict is widespread and can have a significant impact on user ratings of IEQ, therefore, it is a useful base for further study to ensure the validity of IEQ questionnaires based upon recall are not skewed by conflict.

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## References

- Ashkanasy, N. M., Ayoko, O. B. & Jehn, K. A. (2014) 'Understanding the physical environment of work and employee behavior: An affective events perspective'. *Journal of Organizational Behavior* **35**(8), 1169–1184. doi:[10.1002/job.1973](https://doi.org/10.1002/job.1973)
- Ayoko, O. B. & J. Härtel, C. E. (2003) 'The Role of Space as Both a Conflict Trigger and a Conflict Control Mechanism in Culturally Heterogeneous Workgroups'. *Applied Psychology* **52**(3), 383–412. doi:[10.1111/1464-0597.00141](https://doi.org/10.1111/1464-0597.00141)
- Behan, K. (2015) 'Daily Office Wars Revealed in New National Survey Provided by OpenWorks'. Retrieved from <http://www.prweb.com/releases/2015/08/prweb12916617.htm>
- CareerBuilder. (2015) 'Temperature Wars Are Heating Up the Workplace, According to New CareerBuilder Survey'. Retrieved from <http://www.careerbuilder.com/share/aboutus/pressreleasesdetail.aspx?sd=12%2F17%2F2015&id=pr926&ed=12%2F31%2F2015>
- CIPD. (2008) Leadership and the Management of Conflict at Work ( No. October), 21. London: CIPD. Retrieved from <http://www2.cipd.co.uk/NR/rdonlyres/E426E492-7AED-46A6-B8F5-92B9CF9725C5/0/4545Leadershipconflict.pdf>
- Consulting Psychologists Press Inc. (2008) Workplace conflict and how businesses can harness it to thrive, 36. Mountain View, CA: CPP Global. Retrieved from [https://www.cpp.com/pdfs/CPP\\_Global\\_Human\\_Capital\\_Report\\_Workplace\\_Conflict.pdf](https://www.cpp.com/pdfs/CPP_Global_Human_Capital_Report_Workplace_Conflict.pdf)
- Danielsson, C. B., Bodin, L., Wulff, C. & Theorell, T. (2015) 'The relation between office type and workplace conflict: A gender and noise perspective'. *Journal of Environmental Psychology* **42**, 161–171. doi:[10.1016/j.jenvp.2015.04.004](https://doi.org/10.1016/j.jenvp.2015.04.004)
- Dykes, C. & Baird, G. (2013) 'A review of questionnaire-based methods used for assessing and benchmarking indoor environmental quality'. *Intelligent Buildings International* **5**(3), 135–149. doi:[10.1080/17508975.2013.783457](https://doi.org/10.1080/17508975.2013.783457)
- Fisk, W. J., Black, D. & Brunner, G. (2011) 'Benefits and costs of improved IEQ in U.S. offices'. *Indoor Air* **21**(5), 357–367. doi:[10.1111/j.1600-0668.2011.00719.x](https://doi.org/10.1111/j.1600-0668.2011.00719.x)
- Frontczak, M. & Wargocki, P. (2011) 'Literature survey on how different factors influence human comfort in indoor environments'. *Building and Environment* **46**(4), 922–937. Elsevier Ltd. doi:[10.1016/j.buildenv.2010.10.021](https://doi.org/10.1016/j.buildenv.2010.10.021)
- Hedge, A. (1996) 'Addressing the psychological aspects of indoor air quality'. *The 1st indoor air quality seminar*.
- Kinman, G. & Jones, F. (2005) 'Lay representations of workplace stress: What do people really mean when they say they are stressed?' *Work & Stress* **19**(2), 101–120. doi:[10.1080/02678370500144831](https://doi.org/10.1080/02678370500144831)
- Rahim, A. (1992) 'Managing conflict in organizations'. In: *Construction conflict management and resolution* (P. Fenn & R. Gameson, eds.), 370–379. London: E & FN Spon.
- Ursin, H. (2014) 'Brain sensitization to external and internal stimuli'. *Psychoneuroendocrinology* **42**(0306), 134–145. Elsevier Ltd. doi:[10.1016/j.psyneuen.2014.01.008](https://doi.org/10.1016/j.psyneuen.2014.01.008)



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*Design to Thrive*

## Bio-environmental zones of Paraguay. Bioclimatic definition for design

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**Abstract:** This work was realized with the aim to determine the bio-environmental zones, of the Oriental and Occidental regions of the country, taking into account the annual climatic variations during the period of 30 years. The aim is to obtain adequate guidelines and design parameters, to improve the possibilities of habitability and hygrothermal comfort of building interiors, according to the climatic regions. For the analysis there were defined two periods, winter (July), where it is confirm the demand of energy for the heating and summer (January), with the indexes of corrected effective temperature (CET), a scale of thermal sensation where the relative humidity affects the temperature. According to the results, compared with levels of comfort required in habitability, there were proposed strategies to improve and mitigate such discomfort. They will be able to be used as a tool for urban planning and for the development of architectural projects of low environmental impact, as well as to transform and adapt the existing buildings, based on criteria of environmental sustainability and energy efficiency, in order to reduce the energy dependency on the electrical network.

**Keywords:** Energy efficiency, climatological variables, bio-environmental design.

### Introduction

This study defines the bio-environmental areas of the Eastern and Western Regions of Paraguay, with criteria to be considered in the architectural design, regarding the hygrothermal comfort of the interior spaces, to optimize the use of energy for air conditioning and natural lighting indoors lighting indoors. Therefore, the buildings are designed with specific guidelines to consider, in order to adapt these to the area of use.

The bio-environmental zoning of a territory, as in this case, is based on the reciprocity between the human being, the climate, the site. Its natural resources, geographical position, and the building are related to the climate variations during the year. The purpose of understanding the bio-environmental different zones is due to the need to design and apply bioclimatic strategies according to each zone, focused on energy efficiency in new buildings and/or refurbishing existing ones.

The work has as antecedent the procedures performed to define the bio-environmental zones in the IRAM Norms 11603-2012, of Argentina on the same subject.

It defines the mapping, for each bio-environmental zone, characterized by the difference of climate, temperature, humidity, winds, precipitation, solar radiation in order to adapt to the climatic incidences in the specific site, according to the geographical location, with general design parameters.

The objective is to determine the bio-environmental zones in the Eastern and Western Region, , considering the annual climatic variations of each defined area, over a period of 30 years, to establish architectural design strategies with focus on energy efficiency.

These guidelines can be adopted voluntarily by architects, engineers, builders, and by local governments, through municipal ordinances; with specific application in each one.

The approach bio-environmental is used as a theoretical support for the relationship between the human being, the environment and the building or built space. The concepts of the comfort triangle (Evans, 2000) are used for the analysis process. As well as the concept of comfort zone according to the weather and humidity conditions are situated in a thermal well-being, they establish the Comfort area, (Gonzalo, 2003).

## **Method**

The investigation of the research is based on the evaluation of climatological data in summer and winter over 30 years, by day, by month and by year. Using the climatological data of the National Meteorological Office and processing selected variables.

The geographic areas that present similar climatic conditions are determined, which are used for the application of bioclimatic strategies that allow the development of designs that minimize the use of electrical energy of the network. The zones are defined, and the bio-environmental strategies for the buildings suggested, including thermal inertia of materials, use of solar radiation, prevailing winds, rains, site vegetation, among others.

For the determination of bio-environmental zones are specified criteria. The Effective Temperature is used in summer for warm weather and in winter for cold weather. We analyze the values of the month of January (summer in the southern hemisphere) and July (winter) through a period of thirty years, (Dry Bulb Temperature, T. Wet Bulb, Average Radiant T., and Air Velocity, Thermal amplitude, Difference of oscillation between Max Temperature and Min Temperature. Wind; Direction-frequency, Speed-frequency). Hours of sun (monthly average), % in hours that direct solar radiation is available.

The geographic position is an important variable to be mentioned, as high as this can reach (present altitude), the maximum temperature will tend to decrease at the rate of 0.9 °C for each 100 meters of elevation, in this research this variable is not used, although it should be used for each Municipality.

## **Bio-environmental zones formulations**

For the definition, some parameters are specified and cross-referenced, the software 'Surfer' is used in mapping and 'R' is used for statistical management. The research was carried out together with the National Meteorological Office.

The particularity common to the whole country is its metathermic condition, Pasten (2015). The Eastern Region is characterized by a metathermic climate, rainy for the most part and only in two ends presents different peculiarities of sub humid. It is defined according to climatological characteristics; very warm-humid, very warm-dry, warm-wet, warm-dry, temperate-humid, temperate-dry.

The climate of the Eastern Region of Paraguay is characterized by very humid summers and winters with variable humidity, between dry and humid. The climate of the Western Region presents areas ranging from Warm-humid, warm-dry, to warm-very dry. The statistical data were analyzed for a period of 30 years. The variables were defined for summer and for winter, are specified in Tables 1, 2.

## Weather data processed in summer and winter

Table 1. Weather data in summer. Paraguay

Station	Lat	Lon	ASNM	Max abs	Min abs	Max med	Min med	Med	Temp ocio	prcp	Hr	Helio
Mcal.Estigarribia	-22.0	-60.6	167	43.6	9.8	35.1	22.5	28.4	20.7	115.5	66.9	7.7
Puerto Casado	-22.3	-57.9	78	42.0	10.2	33.9	23.1	28.2	21.9	150.0	71.4	7.9
Pedro J. Caballero	-22.6	-55.8	563	39.4	9.0	29.7	20.2	24.4	19.6	176.5	76.9	7.3
Concepción	-23.4	-57.4	75	41.6	11.4	33.5	22.5	27.5	21.9	150.6	74.1	8.0
Salto del Guairá	-24.0	-54.4	297	40.8	10.0	31.6	21.0	25.5	21.1	161.6	78.8	7.6
Asunción	-25.2	-57.5	83	41.7	10.2	32.9	22.2	27.2	20.9	140.1	71.1	7.9
Villarrica	-25.8	-56.4	163	40.4	8.4	32.2	20.8	26.3	21.0	152.5	75.0	8.0
Minga Guazú	-25.5	-54.8	247	40.2	8.2	32.3	21.1	25.9	20.9	175.7	76.7	8.3
Pilar	-26.9	-58.3	58	42.1	9.8	32.6	21.8	26.9	21.1	147.8	72.7	8.1
Caazapá	-26.2	-56.4	142	43.7	10.0	31.7	20.8	25.7	19.7	137.6	71.6	8.1
Encarnación	-27.3	-55.9	90	42.0	7.0	32.1	19.9	26.1	20.5	160.0	73.9	6.3

Table 2. Weather data in winter. Paraguay

Station	Lat	Lon	ASNM	Max abs	Min abs	Max med	Min med	Med	Temp ocio	prcp	Hr	Helio
Mariscal Estigarribia	-22.0	-60.6	167	40.8	-4.5	27.0	13.7	20.0	12.3	15.4	65.3	5.5
Puerto Casado	-22.3	-57.9	78	39.0	-0.4	26.7	15.1	20.5	14.6	43.9	71.8	5.9
Pedro J. Caballero	-22.6	-55.8	563	36.2	-1.8	24.4	13.4	18.2	12.4	67.5	71.6	7.2
Concepción	-23.4	-57.4	75	40.2	-2.8	25.8	13.8	19.2	14.1	49.7	75.3	5.7
Salto del Guairá	-24.0	-54.4	297	38.0	-2.8	24.5	12.2	17.4	13.6	86.6	81.2	6.2
Asunción	-25.2	-57.5	83	38.5	-1.2	23.9	13.8	18.3	12.9	60.6	73.5	5.4
Villarrica	-25.8	-56.4	163	36.0	-3.0	23.7	12.5	17.6	13.0	92.2	76.9	5.9
Minga Guazú	-25.5	-54.8	247	36.2	-3.0	24.1	12.4	17.3	13.1	106.1	79.4	5.8
Pilar	-26.9	-58.3	58	37.0	-2.2	22.4	11.9	16.7	12.6	53.1	79.1	5.7
Caazapá	-26.2	-56.4	142	37.4	-2.0	23.0	12.3	16.9	12.9	96.2	79.5	5.7
Encarnación	-27.3	-55.9	90	37.5	-4.5	22.5	10.6	16.4	12.5	110.3	80.2	4.1

## Equivalent temperatures for summer and winter defined, of the Meteorological Station.

The stations that are in the Eastern and Western regions of the country. Table 4. They refer to Figure 3 and 4 of maps.

Table 4. Equivalent temperature for summer and winter.

Lon	Lat	ASNM	Name of the Meteorological Station	TE Summer	TE Winter
-60.62	-22.03	167	Aeropuerto de Mcal. Estigarribia	50.3	12.8
-57.94	-22.28	78	Puerto Casado	49.2	14.7
-55.83	-22.64	563	Aeródromo de Pedro Juan Caballero	41.9	10.8
-58.79	-23.50	98	Pozo Colorado	51.3	12.0
-57.43	-23.44	75	Aeródromo de Concepción	49.2	12.1
-54.63	-24.03	297	Aeródromo de Salto del Guairá	46.3	11.2
-57.51	-25.24	83	Aeropuerto Internacional "Silvio Pettrossi"	46.8	12.6
-56.44	-25.75	163	Villarrica del Espíritu Santo	46.6	10.8
-54.84	-25.46	247	Aeropuerto Internacional Guarani, Minga Guazú	47.3	10.9
-58.32	-26.88	58	Aeródromo de Pilar	46.9	11.0
-57.13	-26.67	131	San Juan Bautista	45.6	10.5
-56.35	-26.18	142	Caazapá	44.7	11.9
-55.90	-27.30	90	Encarnación	46.1	9.9

## Example Equivalent Temperature for the city of Asunción. According to the methodology of Quayle y Steadman, 1999

As an example of thermal comfort in summer and winter, the equivalent temperature index (ITE) (Quayle y Steadman, 1999) and Humidex (Meteorological Service of Canadá, 2009) was used for the city of Asunción. The ITE was used for the winter months (June, July and August) of the period 1961- 2013. The Humidex was calculated for the summer months (December, January and February) of the seasons 1961- 2013.

The ITE was calculated by the following formula:

$$TE = 1.41 - 1.162 V + 0.980 T + 0.0124 V^2 + 0.0185 VT$$

Where T the average air temperature ( $^{\circ}\text{C}$ ) and V is the wind speed (m/s).

The index Humidex was calculated by the following formula:

$$TH = T + 5/9 (e - 10)$$

where e is the vapor pressure (hPa). This was calculated by the following equation:

$$e = 6.112x(10)^{[7.5 T / (237.7 + T)]} \times H/100$$

where H is the air humidity (%). The degree of discomfort according to the Humidex index is shown in the following Table.

Table 3. Humidex comfort index. Source: Meteorological Service of Canada, 2009.

Range	State
$\leq 29^{\circ}\text{C}$	Confortable
30 – 39°C	Some discomfort
40 – 45°C	Great discomfort, avoid efforts
$\geq 45^{\circ}\text{C}$	Danger

The "comfortable" range it's considered very high, for that reason is proposed 24  $^{\circ}\text{C}$ . However, the comfort range is defined by the comfort triangle (Evans, 2000), with temperature from 18  $^{\circ}$  to 28  $^{\circ}\text{C}$  (24°C confortable), a relative humidity, between 20 – 80%. Only humidex was used for summer, which includes humidity and temperatures, and the equivalent temperature index was used for winter, which includes wind speed.

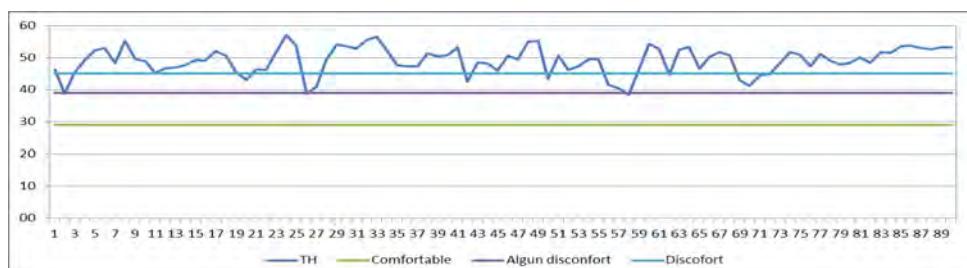


Figure 1. Comparison of summer (December, January, February 2013), Humidex Index

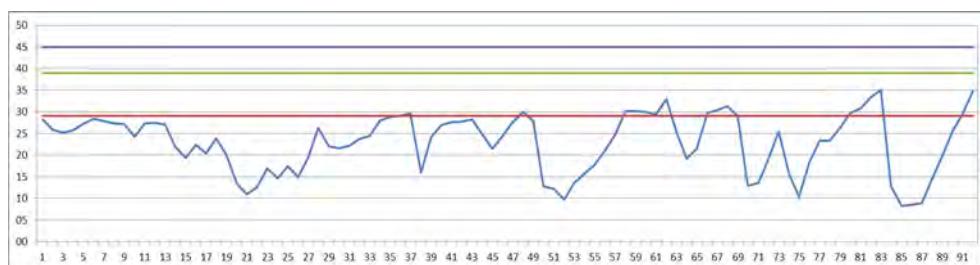


Figure 2. Comparison of winter (June, July, August 2013), Equivalent temperature index

## Results

### Example of Asunción

In summer the thermal sensation is located above the comfort range, in that sense an architectural design must be foreseen that can serve as protection of the exterior and reduce the discomfort, anticipating strategies in both design and materials and construction.

### Equivalent temperature for winter and summer

In winter, the thermal sensation decreases considerably with the variant of the wind, thus, the interior spaces must include insulation of the enclosures to avoid leaks.

In winter, the prevailing winds SE-S are very influential. In summer, the thermal sensation is very high in some areas of the country, according to the map of TE in both regions, due to the presence of humidity in the environment, it facilitates the feeling of discomfort. In summer, the prevailing winds NE-SW are very warm and weak, it is necessary to have designs that guide and generate air currents indoors to dehumidify the surroundings and keep them cool. Devices like inner sunshades or outer air chambers are recommended. Above all, the thermal inertia of materials must be taken into account.

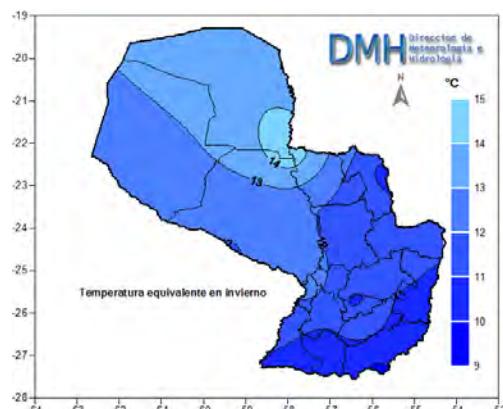


Figure 3. Map of the equivalent temperature for the Paraguay Regions winter (july).

The values were calculated using the first equation which includes the minimum temperature and the wind speed. With the wind variable, the thermal sensation of the most exposed areas is the south of the territory. Figure 3.

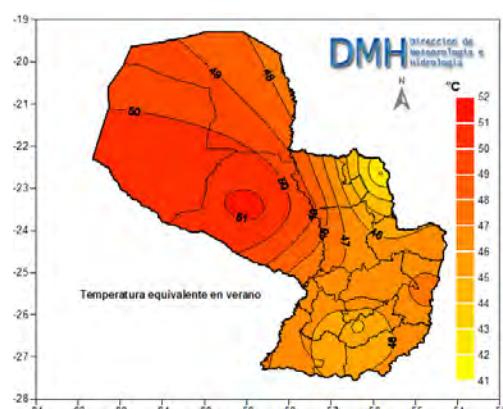


Figure 4. Map of the equivalent temperature for the Paraguay Regions summer. Elaboration: Max Pasten.

The differentiated climates with variables of maximum temperature and relative humidity for the regions are: very Warm-humid, very warm-dry, sub-humid, warm humid, warm-humid rainy, warm-humid, with microclimatic variation, tempered-warm, warm-dry.

The Energy demand for the heating and cooling is confirmed.

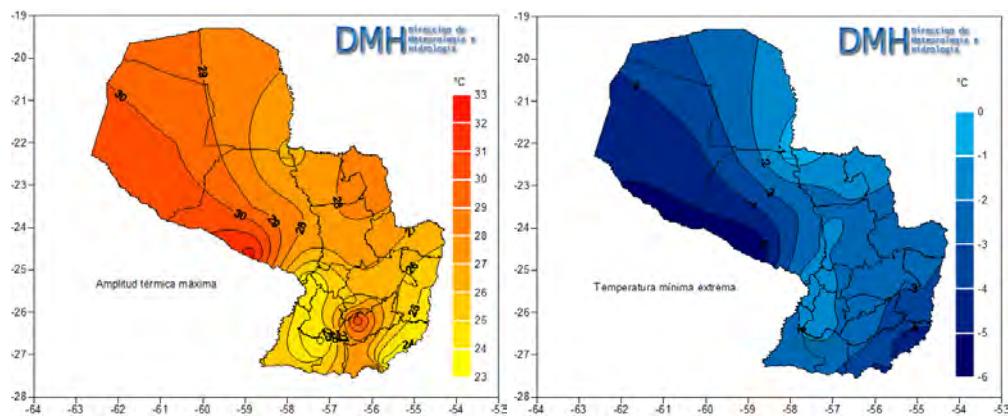


Figure 5. Map of maximum thermal amplitude in the period between 1972 and 2013.  
Figure 6. Map of minimum thermal amplitude extremes in the period between 1972 and 2013.

Elaboration: Max Pasten. Direction of Meteorology.

In this case the daily thermal amplitude was calculated ( $T_{max} - T_{min}$ ) and the maximum value and the date of the occurrence were selected. The other case was selected from the database, the lowest temperature recorded in each of the meteorological stations.

### Different bio-environmental zones, defined in the Eastern and Western Region

Table 5. Bio-environmental zones, according to, defined climates in the Western Region

Nº	Climates	Estimated% ratio	% HR Summer	Western R. Departments
1	Very warm-humid	20 %	66,9/71,4	Pte. Hayes, Alto Paraguay
2	Very warm-dry, sub-humid	42 %	66,9/65,3	Alto Paraguay, Pte. Hayes, Boquerón
3	Very warm-Dry semi-arid	38 %	65	Boquerón, Pte. Hayes

Table 6. Bio-environmental zones, according to defined climates in the Eastern Region

Nº	Climates	Relation of %	% HR summer	Eastern Region (Departments)
1	Very warm-humid	7,5 %	74,1/75,3	Concepción, San Pedro
2	very warm-dry, subhumid	5 %	74,1/65,3	Concepción
3	Warm-humid	63 %	76,9/76,7	Concepción, San Pedro, Canindeyú, Alto Paraná, Cordillera, Central, Caaguazú, Guaira Paraguarí, Ñeembucú
4	Warm-humid rainy	3 %	76,7/78,4	Alto Paraná, Caazapá
5	Warm-humid, with microclimatic variation	18 %	71,6	Caazapá, Itapúa, Guaira, Paraguarí, Misiones, Amambay
6	Tempered-warm, humid	4 %	76,9/71,6	Amambay

The resulting values guide us in terms of the degrees we must reduce in summer and winter in terms of hygrothermal comfort range; the degrees that we need to increase within the spaces to reach the values of such comfort. We can already predict the situation of the site where the building will be installed, considering the studied variables, the incidences are the same for the design. Preventing winds according to altitude, relative humidity of the site, materials to be implemented, etc.

Table 7. Proposal of Strategies of architectural design, for the buildings, in bio-environmental zones of Warm - Humid climate\* of the Eastern Region and Warm –Dry subhumid\* climate of the Western Region

Warm-Humid *	Strategies
Orientation	N-NE y SE, avoid openings orientation to W. Locations with orientation to E, with minimum openings.
Ventilation	Cross ventilation, preferably N-S, and all possible locals, even the ceilings with outside banners by convection. (Provide protection against insects). Design with the prevailing winds of the Region, NE_SO. Perform channelling air with architectural design. The air currents rebound the use area of people in interior spaces. Gathering of winds of masses of water, forests. Define the relation of room's proportions; the interior height, with chimney effect strategy for the extraction of hot and humid air. Natural refrigeration.
Colors	Surrounding ceilings and walls oriented to E-W; light colors.
Materials and construction system.	Thermal mass recommended (200-300 Kg/m2. Iram Norm) Increased thermal inertia, with extreme temperatures (massive brick masonry, stone, adobe). Materials for enclosures (top, side, bottom cover) Thermal and acoustic insulation. Low emission glasses.
Sunlight	Winter, minimum 2 hours of sunlight in the rooms. Summer, avoid direct sun, sun protection to W from E, -45/+21° y -123°/201°. (Czajkowski, 2009)
Parasols, eaves, furs	They will be used especially in openings oriented to N-E-W.
Vegetation	In the environment: create shadows, air currents in order to lower the outside temperature.
Humidity. Water	Proximity of water masses (lake, rivers), channeling breezes, 75% less.
Altitude	Every 100 meters, decrease by 0.9 ° C.
Thermal amplitude	Less than 14 ° C is not appreciable.
Heat islands	Handling and reducing heat islands of the building or others, will help the interior comfort.
Hygrothermal comfort triangle (Evans,2000)	Temperature; 18-28 ° C. RH; 20-60%. Define the range of the site compared to comfort.
Warm –Dry Subhumid *	Basic strategies
Orientation	N-NE y SE, avoid openings orientation to W.
Ventilation	Selective cross-ventilation, preferably N-S, southern hemisphere. Design with the prevailing winds of the Region, NE-SW. Carry out air channels with architectural design. The air currents are in the use area of people. Take advantage of temperature differences, do not allow air to enter from 40 ° C to 50 ° C, during the day, with greater restriction of openings, but allow the entry of night air to less than 20 ° C, for cooling
Colors	Clear colors in wraparound ceilings and walls oriented to the E-W.
Materials and construction system.	It is recommended a large thermal mass, to obtain greater thermal inertia, with extreme temperatures (masonry of solid bricks, stone, adobe)
Sunlight	Winter, minimum of 2 hours of sun light.
Parasols, eaves, furs	They will be used especially in openings orientated to the N-E-W
Building layout. Humidity. Water	Generating massifs and open space to the interior, with atrium or inner patio, Design evaporative cooling and humidification, with air and water collection towers, when it is above 28 ° C and under% humidity less than 30%
Thermal amplitude	Western Region is greater to 14 ° C, it is noticeable in summer and lower to 9 ° C in winter, it is used to provide greater thermal inertia.

## Conclusions and recommendations

The bio-environmental zoning of a territory enables;

- Identification of the characteristics of each defined area and its particularities in relation to comfort
- The knowledge of meteorological variables and the forecast of unfavorable situations

- Improve them to achieve hygrothermal comfort in the different areas
  - There must be a specific study of bio-environmental zone in each locality, to know the climatological variables and how they interact with their geographical position.
- It is an instrument at a regional level, which:

- Exposes the climatological situations in relation to the specific site and the natural resources of the area.
- At the same time, it guides the design strategies and serves as the basis for the design of architectural spaces.

Recommendations; emphasize the importance of carrying out a more detailed study of the climatological components in each District, to deepen the knowledge of the bio-environmental zones that may be contained in them, proposing after this a set of guidelines for the urban sector and the rural one as well.

Considering that the energy consumption of mechanical air conditioning has increased recently in several cities in Paraguay, it is suggested to continue this line of studies.

## References

- Czajkowski, J.(2009). *Arquitectura sustentable*. Arq. N°3. Buenos Aires: Clarín.
- Chávez, R. y Fuentes, V. (1986). *Arquitectura bioclimática y energía solar. Viento y arquitectura*. México: Universidad Autónoma Metropolitana.
- De Schiller S. (2002). *A renewed focus on the design process, Sustainable building*.
- Edwards, Brian. (2008). *Guía Básica de la sostenibilidad*. Segunda edición. Ed. G.G. Barcelona.
- Evans, J.M., De Schiller, S. (1991). *Diseño bioambiental y arquitectura solar*. Segunda Edición. Buenos Aires: FADU-UBA.
- Evans, J.M. (2000). *Bioclimatic design resources. The 'Mahoney tables' and the 'Comfort triangles'*. Buenos Aires: FADU-UBA.
- Gauzin-Müller, D. (2002). *Arquitectura ecológica*. Barcelona: Gustavo Gili.
- Gonzalo, G. E. (2003). *Manual de Arquitectura Bioclimática*. Buenos Aires: Nobuco.
- Grinberg, C. *Climatización*. Arq. N°4. Buenos Aires: Clarín.
- IRAM. (2011). Norma 11603. Acondicionamiento térmico de edificios. Clasificación bioambiental de la República Argentina.
- Ken Yeang. *El rascacielos ecológico*. Gustavo Gili.
- Ken Yeang. (1999). *Proyectar con la naturaleza. Bases ecológicas para el proyecto arquitectónico*. Barcelona: Gustavo Gili.
- Melián, M.G. (2016). *Calificación de la edificación sustentable para la Región Oriental de Paraguay*. Universidad Católica Nuestra Señora de la Asunción. (Unedited) Asunción.
- Pasten, M. (2014). *Climas del Paraguay. Gerencia de Climatología e Hidrología*. DINAC. Asunción.
- Rosas, M., Garrido, N. (2008). *Ahorro, eficiencia y gestión de la energía. Módulo 8. 2º Edition*. Barcelona: Cátedra Unesco e sostenibilidad de la UPC.
- Serra , R. y Coch, H. (2005). *Arquitectura y energía natural*. México: Alfaomega.
- Serra, R. (1999). *Arquitectura y Climas*. Barcelona: Gustavo Gili.
- Tortajada, R, Hansson, C. (2008). *Hacia una arquitectura sostenible 2*. Valencia: ICARO-CTAV.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Influence of thermal insulation performance of housing on lifestyle of residents - Focusing on window performance -

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**Abstract:** In recent years, high thermal insulation of housing has become increasingly popular because energy saving in residence is required for a global environment. However, the influence of high thermal insulation of housing on the life, awareness and behaviour of residents has not been clarified. Therefore, we conducted a questionnaire and actual measurement survey targeting the metropolitan area of Tokyo during summer and winter to examine the relationship between the thermal insulation performance of housing and the lifestyle of the residents. In this study, we focused on the window which has big heat transfer and estimated thermal insulation performance of housing depending on the kind of window glass and window sash. The main results clarified in the above method analysis are as follows: 1) As the thermal insulation performance increased, the thermal satisfaction in all rooms became higher both during summer and winter. 2) As the thermal insulation performance improved, the temperature difference in the entire room decreased and the active area of residents in the house tended to increase both during summer and winter.

**Keywords:** Thermal insulation performance, Indoor thermal environment, Life style, Questionnaire survey, Measurement survey

### Introduction

In response to environmental problems such as global warming, various countermeasures have been taken in industry, transportation, household sector, etc. in Japan. In particular, efforts to conserve energy in buildings have been regarded as essential, and a policy was obligated to comply with energy conservation standards for all new houses and buildings by 2020 (MLIT, 2016). Thus, high insulation of houses and use of natural energy will be promoted, and energy conservation and thermal comfort are expected to improve. Besides the hardware aspect of improving building performance, soft aspects, such as consciousness of energy conservation and behaviour of households have also been emphasised in recent years as research on energy conservation in houses, and many researches related to them have been made (Yoshino et al, 2006). However, there are few case studies focusing on the outer shell performance of houses, the consciousness and livelihoods of residents (Sato, 1994).

And it is thought that it is necessary to clarify the influence of high insulation of houses, which will increase in the future, on the life of the household. Therefore, in this study, under the hypothesis that -the difference in the thermal insulation performance of the residence brings about a change in the lifestyle of the residents-, actual measurements and questionnaire surveys are conducted for the houses built in the

metropolitan area in Japan, and it aims to examine the relationship between the two. In addition, we devised to evaluate the thermal insulation performance of the house by the kind of window glass and window sash and applied it to our analysis.

## **Survey Summary**

### ***Measurement survey summary***

To ascertain differences in indoor thermal environments due to differences in thermal insulation performance, actual measurements were conducted in winter. The survey was conducted at a total of nine detached and apartment houses built in the metropolitan area of Japan. The implementation period was from January 27 to February 19 in 2016. Measurements were conducted in the living room, bedroom, washroom, and outdoor temperature and humidity of each residence at intervals of 10 minutes. And the surface temperature was measured in the living room and the bedroom. Table 1 shows a summary of this survey.

Table 1. Overview of the measurement survey

Measuring type	Measuring interval	Measuring place	Measuring room				Measuring period
			Living room	Bed room	Wash room	Outside	
Temperature and humidity	10 minute	Floor level +100 mm	○	—	○	○	2016/1/27-2/19
		Foor level +1000 mm	○	○	○		
		Ceiling level - 100 mm	○	—	—		
Surface temperature	10 minute	Window	○	○	—		2016/1/27-2/19
		Ceiling	○	○			
		Wall	○	○			
		Floor	○	○			

### ***Questionnaire survey summary***

The questionnaire survey was conducted in summer and winter. This survey was conducted by mail in summer and by both mail and e-mail in winter. In this survey, residents were asked about various housing attributes, such as family composition, building age and total floor area, and their thermal environment satisfaction, behaviours or customs, lifestyle consciousness and so on. Table 2 describes the outlines of the surveys.

Table 2. Overview of questionnaire survey

Implementation season	Summer		Winter		
	Mail		Mail		Web
Survey method	Household	Family members	Household	Family members	Family members
Target	136	253	118	211	694
Total	2015/8/20- 9/5		2016/1/10- 1/24		2016/1/22- 1/24
Survey period	Family structure, Housing attribution				
	Thermal environment satisfaction , Habit or Behaviour, Life consciousness, Life action range, Thermal sensation or Comfortable sensation				

### ***Evaluation of thermal insulation performance of housing***

To determine differences in thermal insulation performance, information of the thermal insulation property of the target housing is necessary. Therefore, data such as heat loss

coefficient and heat transmission rate, which are indices of the thermal insulation performance of houses, are required. However, in many cases, residents themselves are unaware of this information and obtaining these details is difficult. So it is thought that it is necessary to evaluate the thermal insulation performance of houses in a simple way. Therefore, in this study, we focused on an opening that contributes significantly to the thermal-insulation performance of a house: the window glass and window sash. Also, since the architectural forms of detached and apartment houses differ, the two are roughly classified. From the above, the level of thermal insulation performance is simply classified. In terms of responses to the questionnaire survey, those specifying housing type and window glass and sash types were considered valid responses. The corresponding classification levels are shown in Table 3.

Table 3. House performance division

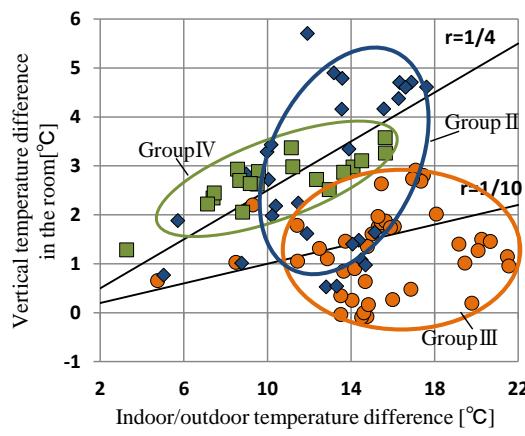
Classification	I	II	III	IV	V	VI
Thermal insulation performance	Low	Middle	High	Low	Middle	High
Architectural forms	Detached house			Apartment house		
Window glass	Single	Pair	Low-E pair or Triple	Single	Pair	Low-E pair or Triple
Window sash	Steel or Aluminum	Aluminum	Aluminum and Plastic	Steel or Aluminum	Aluminum	Aluminum and Plastic
Effective number of respondents	Summer mail	54	47	22	81	21
	Winter mail	35	47	11	60	13
	Winter e-mail	142	78	6	172	53
						1

### Actual measurement results in winter 2016

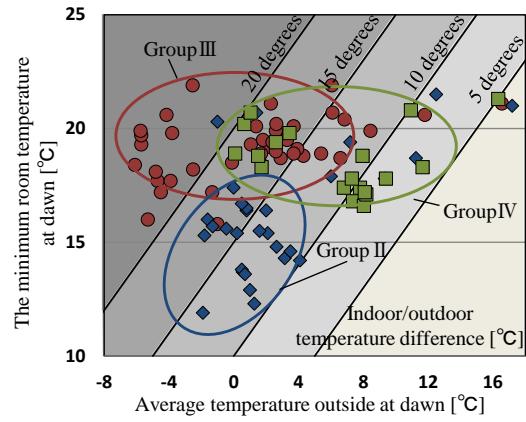
Figure 1 shows the relationship between the vertical temperature difference in the living room and the indoor/outdoor temperature difference for each dwelling unit surveyed. The temperature difference between the top and bottom of the living room was calculated from 100 mm above the floor and 100 mm below the ceiling, and the inside/outside temperature difference was calculated from the temperature difference between the living room 1000 mm and the outside air. In addition, the temperature difference coefficient 'r' was obtained by dividing the room temperature difference by the indoor/outdoor temperature difference. Group III houses presented a large indoor/outdoor temperature difference, but their room temperature difference was as small as 0–2 degrees. By contrast, houses in groups II and IV showed a room temperature difference of about 2–4 degrees. The results above confirm that a good indoor thermal environment exists in houses with high thermal insulation performance.

The relationship between the minimum ambient temperature and the average ambient temperature at dawn is shown in fig.2. Here, the minimum room temperature was taken 1000 mm above the floor of the living room. In group II, the lowest room temperature at dawn is distributed around 15 degrees, while in group III, it is distributed around 20 degrees.

These results indicate that a good indoor thermal environment is maintained in houses with high thermal-insulation performance, even in cold periods such as dawn.



**Fig.1**  
Relationship between vertical temperature difference in the living room and indoor/outdoor temperature difference



**Fig.2**  
Relationship between the minimum room temperature and the average temperature outside dawn

## Results of the questionnaire survey

### Room-by-room thermal satisfaction

A summary of average value of thermal satisfaction of each room in summer and winter is shown in fig.3. Satisfaction was rated on a scale of 1 to 5, with 1 indicating high dissatisfaction and 5 indicating high satisfaction. The figure demonstrates that detached and multi-unit households with high thermal insulation performance in each room reported greater thermal satisfaction. It is also clear from the average level of satisfaction of each room that improvement in heat insulation performance leads to an increase in thermal satisfaction. Thus, improvements in thermal insulation performance contribute to improvements in the thermal environment of whole rooms



**Fig.3** Average thermal satisfaction of each room (Left: in summer; right: in winter)  
(Scale : 1.Highly dissatisfied ← 3.Neutral → 5.Highly satisfied)

### Temperature difference between air-conditioned and non-air-conditioned rooms

Figure 4 shows temperature differences between air-conditioned and non-air-conditioned rooms during summer and winter. The rate of answering that it feels a temperature difference is higher in group III in winter. But overall, as the thermal insulation performance becomes higher, the ratio of feeling the temperature difference in both summer and winter tends to decrease. This finding reveals that the thermal environment of air-conditioned and non-air-conditioned rooms was perceived to be about the same, that is, the thermal environment of the whole room became constant, if the thermal insulation performance of the room was high.

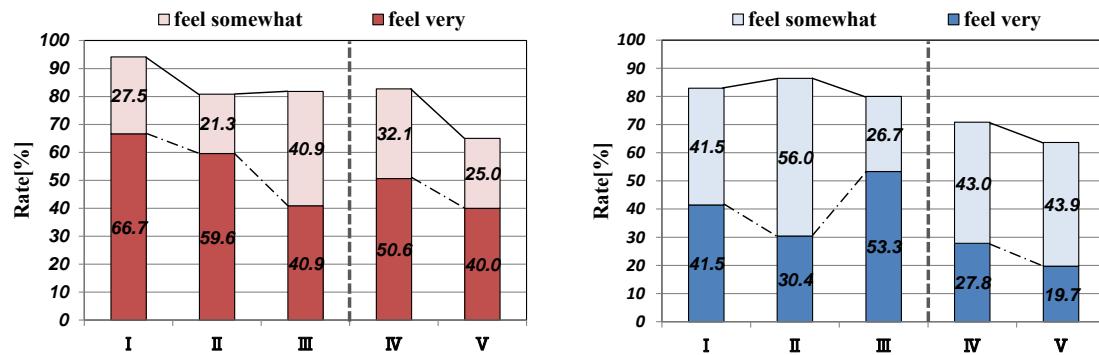


Fig.4 Sensation of temperature difference between air-conditioned and non-air-conditioned rooms  
(Left: in summer; right: in winter)

### Thermal sensation and thermal comfort

Evaluating differences in thermal comfort due to the superiority or inferiority of a house's thermal-insulation performance is difficult because most residential houses use air-conditioning in the living room in summer and winter. Thus, we focused on the washroom, which is a non-air-conditioned room, to understand thermal sensation and comfort in terms of thermal insulation performance. The results for groups I and III are shown in fig. 5. In terms of thermal sensation, the responses of both groups generally indicated feelings of hot in summer and cold in winter. However, group III responses tended to indicate neither very hot nor very cold feelings in comparison with group I responses. As for thermal comfort, the average declared value of group III was higher than that of group I and indicated greater comfort. This result indicates that high insulation performance improved the thermal environment in non-air-conditioned rooms and exerted a positive influence on thermal comfort of residents.

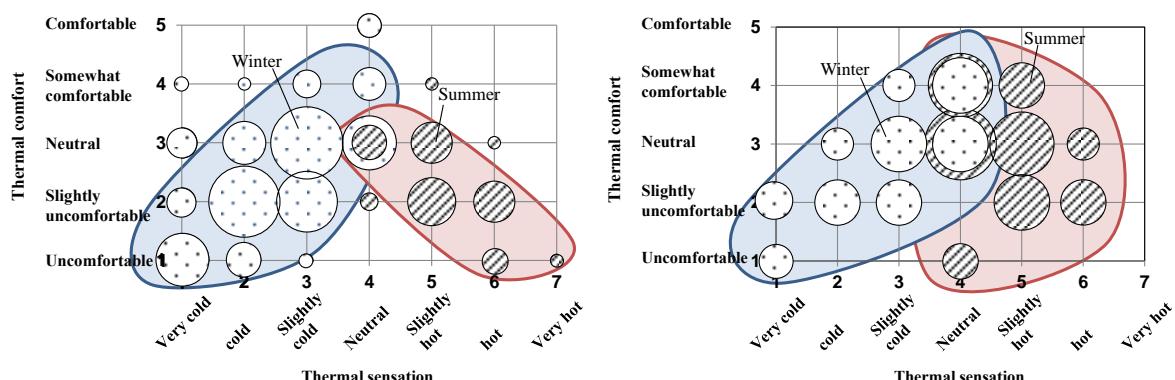


Fig. 5 Relationship between thermal sensation and thermal comfort in the washroom  
(Left: group I; right: group III)

### **Living behaviour range**

Figure 6 demonstrates whether rooms feel hot and unusable during summer and whether rooms feel cold and unusable during winter according to the insulation performance of the house surveyed. There was a tendency that there are many rooms in detached and apartment houses where the residents felt hot in summer and cold in winter with low thermal insulation performance. This result suggests that high thermal insulation performance maintained a certain thermal environment that allowed reduction of the space that cannot be tolerated thermally, which, in turn, increased the range of daily activities of residents. In addition, regarding the summer season, we examine in detail what kind of rooms and spaces it feels hot in the free description form. It was noted that rooms on the second floor in detached houses and kitchens in apartment houses tended to feel hot during summer.

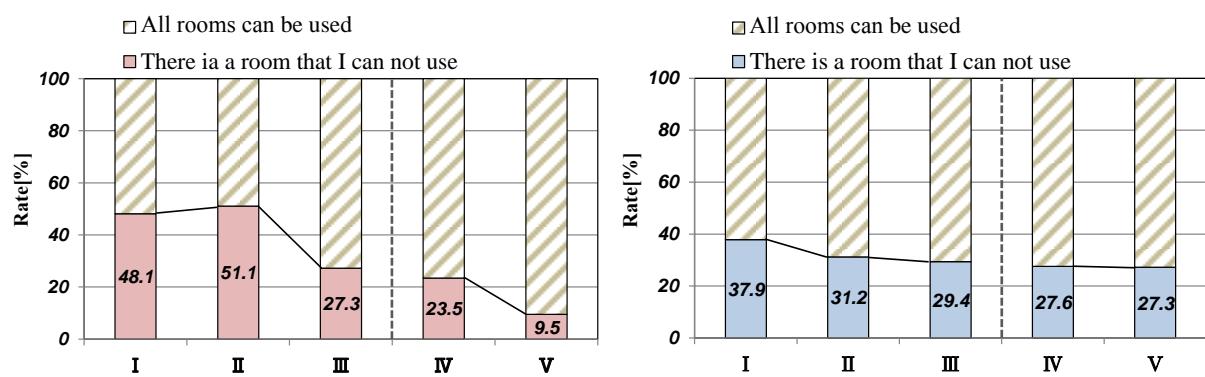


Fig. 6 Ratio of unusable to usable rooms (Left: in summer; right: in winter)

### **Behaviours and customs**

We analysed responses to 21 question items, as shown in Table 4, on daily habits and behaviours during summer and winter. By using correspondence analysis, we examined trends of awareness and behaviours and habits according to thermal insulation performance; the results of these analyses are shown in Figs. 7 and 8. Only the top one in the questionnaire evaluation stage was selected for analysis, and analysis was conducted based on the response ratio. In the questionnaire, five choices were evaluated in summer, and three choices were evaluated in winter. The 'X' marks in the analysis charts represent housing classifications I to V and the '♦' marks represent question items. Furthermore, the closer the distance between an 'X' mark and its '♦' mark is, the stronger the relation is; items close to the 'X' marks are grouped into circles.

In summer, residents tended to demonstrate environmental adjustment behaviours in houses with low thermal insulation performance. By comparison, houses with moderate thermal insulation performance, such as those in groups II and V tended to actively use air conditioning. In summer, residents of houses with high thermal-insulation performance tended to use air conditioners throughout the day; however, in winter, they tended to work towards energy conservation instead of using air conditioners for heat. This finding suggests that houses with high thermal insulation performance provided an environment in which residents wanted to stay in winter. However, in summer, the room temperature adjustment by these residents was insufficient, and it is suggested that the house's performance capabilities could not be fully utilized.

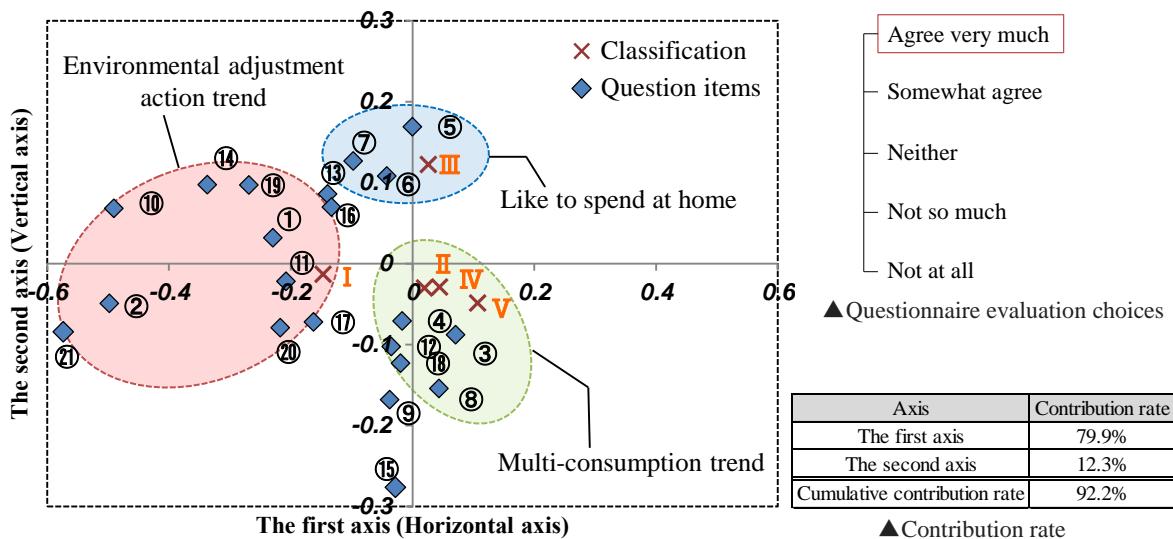


Fig.7 Correspondence analysis in summer

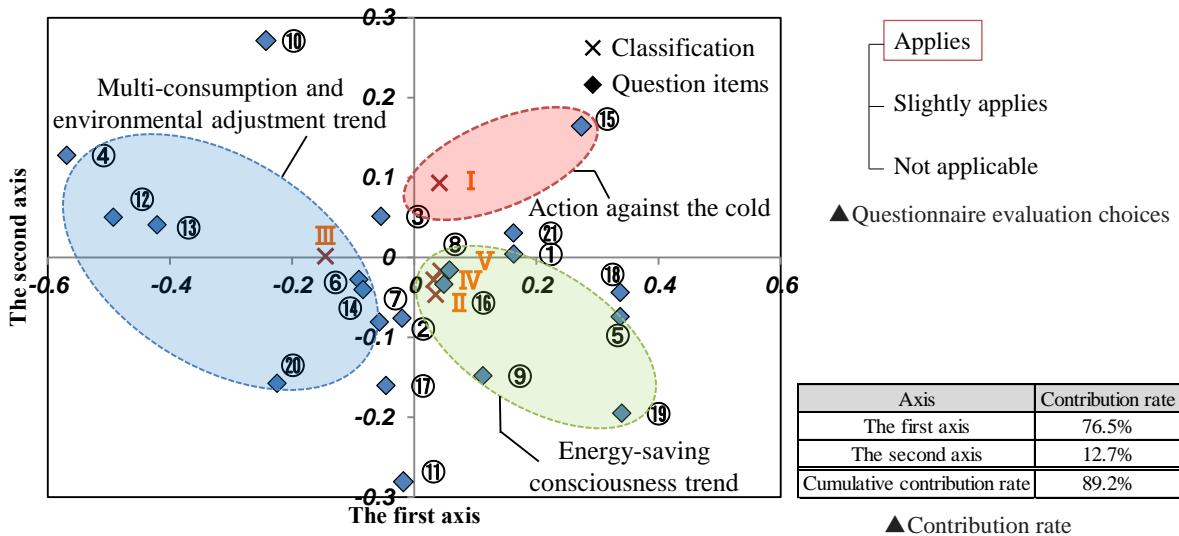


Fig.8 Correspondence analysis in summer

Table 4 Question items

(1)	Morning awakening is better	(8)	Soak in the tub	(15)	Use comfortable goods while sleeping
(2)	Do the housework and work vigorously from morning	(9)	Dispense with shower	(16)	Turn off the air conditioner and illumination faithfully
(3)	Put the air conditioner on after waking up in the morning	(10)	Often cannot fall asleep	(17)	Would prefer not to use the air conditioner
(4)	Leave the air conditioner on during the day	(11)	Thermal environment during sleeping is comfortable	(18)	Use the air conditioner and circulator together
(5)	Open windows to pass as much natural wind as possible	(12)	Leave the air conditioner on while sleeping	(19)	Fine-tune the temperature set for the air conditioner
(6)	Like relaxing at home	(13)	Turn on the air conditioner using the timer setting while asleep	(20)	Get dressed according to the ambient temperature
(7)	Want to spend time at home in holiday because home is comfortable	(14)	Adjust the temperature without using an air conditioner while sleeping	(21)	Adjust the temperature to use blanket when it is cold, to do clothing regulation when it is hot

## **Conclusion**

The thermal insulation performance of houses was classified according to the type of window glass and window sash used, and based on that, the measurement and the questionnaire were summarized. The following conclusions were obtained in this study:

- 1) The indoor thermal environment of a house is greatly influenced by its thermal insulation performance; in high thermal insulation performance houses, the vertical temperature difference inside the house is low, and it maintains room temperature good even at dawn.
- 2) Increases insulation performance decrease the temperature difference between rooms and improve the thermal sensation and comfort of residents, even in non-air conditioned rooms in summer and winter.
- 3) Increasing thermal insulation performance improves the degree of thermal satisfaction in each room of a house in both summer and winter.
- 4) Increases thermal insulation performance decrease the space that cannot be tolerated thermally in both summer and winter, which suggests a wider range of living behaviour in the room.
- 5) Residents in houses with low thermal insulation performance tend to demonstrate more environmental adjustment actions, such as changing clothes depending on room temperature in summer, but countermeasures against cold were forced in winter. On the other hand, residents in houses with high thermal insulation performance tend to actively use cooling in the summer, but it tends to take energy conservation behaviors such as turning off heating and lighting in the winter.

In addition, since the clear trend was shown as described above, the adequacy of substituting the heat insulation performance of the house by the kind of the window glass and the window sash was also proved.

## **References**

- Ministry of Land, Infrastructure, Transport and Tourism in Japan (MLIT), (2016). Overview of the Act on the Improvement of Energy Consumption Performance of Buildings. URL; <http://www.mlit.go.jp/common/001134876.pdf>
- Sato, K. (1994). Thermal environment and living activity, living space of the residential house -study on the planning of detached houses in Hokkaido Part 1-. Prof., Dept. of Architectural Construction, Dohoto University.
- Yoshino, H. et al, (2006). Indoor thermal environment and energy saving for urban residential buildings in China. Tohoku University, Japan. Energy and Buildings, pp.1308-1319.
- Meshino, R. et al, (2016). Research on the Relationship between Thermal Insulation Performance and Life-Style in Residence -part1 examination based on summer investigation for the metropolitan area-, Summaries of Technical Papers of Annual Meeting, A.I.J., D-1, pp.1145-1146.
- Meshino, R. et al, (2016). Research on the Relationship between Building Thermal Insulation Performance and Housing Evaluation by Residents, Proceedings of JSES/JWEA Joint Conference, pp.145-148.



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*Design to Thrive*

## Towards Sustainability in Iranian buildings

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**Abstract:** This paper offers an overview of construction solutions to promote sustainability practices in the Iranian building industry. A special emphasis is given to the reduction of energy and the achievement of comfort to the occupants. Sustainable practices in buildings, often termed as a green construction or sustainable buildings, refer to using structures and processes that should be used to reduce the environment impact and promote the use of sustainable resources during the life-cycle of a building from scratch to design, construction, repairs, renovations, operations, and destruction. This paper examines contemporary design and construction practice in buildings in terms of its sustainable performance. It aims to show that better performance is possible by the adoption of basic environmental design criteria with building materials and components available. This is done by modelling a building with Energy Plus software and measuring its performance. An improved scenario is compared with a typical building for a given construction technology and materials used. The study concludes that the new modelled building employing simple modifications in resources, technology of construction and components (produced and available locally), is more sustainable and energy efficient compared to the traditional building.

**Keywords:** Energy Plus, sustainable building, thermal comfort, sustainable practice, solar panel, improved building

### Introduction

The “building industry” has a substantial impact on the environment. Buildings are responsible for 35% of the primary energy consumption in Iran (2013). Buildings are the main consumers of water, material resources and are major polluters. Sustainable construction practices need to address the consumption of water and energy, the generation of waste, the consumption of construction materials and its incorporation in the structure (Lane, M. B., 2005). This is particularly relevant in Iran, as design and typical construction practices can lead to poor sustainable performance (Arman Hashemi et al., 2015). Buildings are rarely designed to be energy efficient. They rely heavily on cheap fuel, mainly derived from fossil fuels, to cope with extreme weather conditions (both hot summers and cold winters). As a result, buildings tend to be high energy users if they are to guarantee comfort levels to the occupants. Design-based solutions involving relatively simple changes in materials (sourced locally), components and construction technologies (locally produced and available) can be a cost effective and an environmentally sound way to improve the performance of buildings.

## Objectives and method

The main objective of this investigation is to examine contemporary design and construction practices of buildings in terms of sustainable performance. An initial literature review identifies the current state of the art in the construction industry through a case study of a building modelled with EnergyPlus software. The relative performance of two different scenarios are assessed in terms of energy use and comfort levels. The total annual energy consumption of the building is estimated for a set of variable solutions in a conditioned building and overheating is assessed using adaptive comfort criteria for a hybrid solution. Eco-buildings or sustainable construction methods should have low embodied carbon energy, but still be comfortable to the occupants. This helps identify unsustainable construction technologies and components that are typically used in day-to-day construction practices in Iran and suggest better solutions.

## Climate and Energy in Iran

Iran is a vast country and has a variable climate. With two major mountain ranges Zagros and Alborz crossing the country and two seas in the north and south, differences of temperature can vary significantly. Temperatures in Shahrekord can reach -30°C in winter and in Ahvaz in the south reach +50°C, during summer. Lowest average temperatures around 10°C can be found in the north west. Average temperatures can rise to 25-30°C, towards the south east, in the Sistan province. Because of this variable climate, buildings often rely on active cooling and heating systems. Access to vast natural resources results in very low energy prices. Buildings mainly use gas for heating and electricity for cooling. Both are derived from fossil fuels and therefore contribute heavily to CO<sub>2</sub> level in the atmosphere. Besides the problems associated with the environment at a global scale there are also problems of poor air quality and social delight in the neighbourhood.

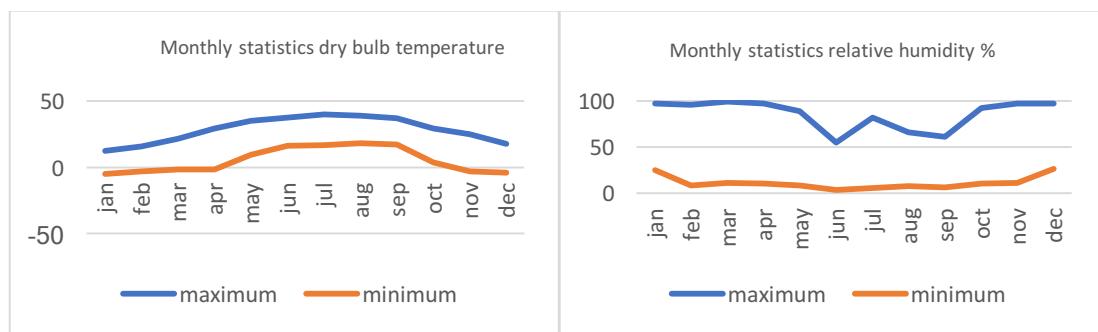


Figure 1. Maximum and minimum monthly statistics for dry bulb temperature and relative humidity for Tehran in Iran, based on data from the Energy Plus weather file for Tehran.

Figure 2 shows that the proportion of share of fossil fuel resources, including natural gas and oil products, comprises the largest share of energy resources in the building sector. Natural gas and petroleum products account for 66% and 20% respectively, electricity 13% and renewable energies just 1%. This resource distribution is contributing to high CO<sub>2</sub> emissions and is aggravating global warming. Increasing renewable energy sources both at the energy supply and at the building level are needed.

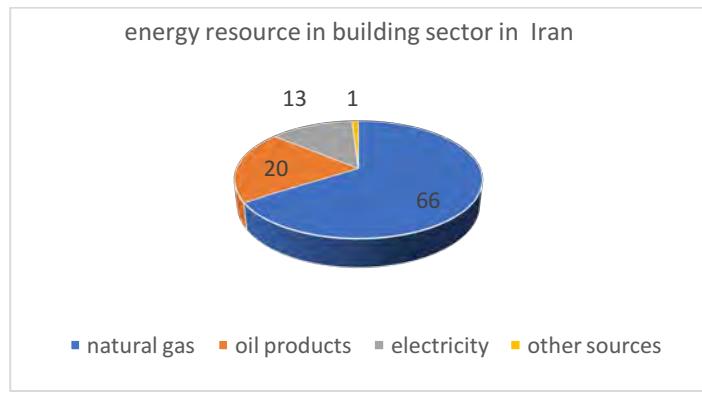


Figure 2. Energy use distribution in the building sector in Iran. Source: EPO (2010).

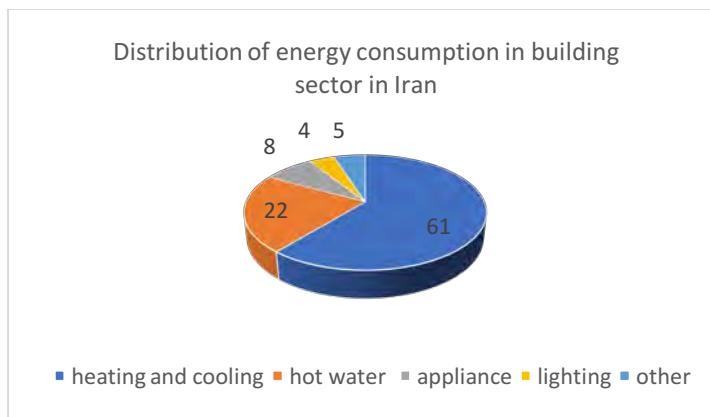


Figure 3. Distribution of energy consumption in the building sector (both domestic and services).  
Source: EPO (2010).

Figure 3 shows the share of the different uses for energy in buildings in Iran. Heating, cooling and hot water account for 83% of the overall usage. It is therefore important to address sustainable solutions that can significantly reduce the energy use (e.g. more insulated envelope and efficient systems) and utilise energy from renewable sources (e.g. solar thermal panels for DHW). Appliances account for 8%, lighting 4% and other elements for 5%. Promoting more efficient light and equipment solutions can still have a significant impact on the energy consumption.

### **Building practices and moving towards sustainable solutions**

A literature review established that current design and typical construction solutions result in buildings with poor sustainable performance (Bartke, R. W., 1973; Azizi, M. M. et al., 1995; Brockerhoff, M. & Brennan, E., 1998; Aghili, J., 2001; Asheim, B. et al., 2007; Shahraki, 2014).

Sustainable development and associated construction practices require good building design and planning in new towns. Buildings need to be adapted to the local climatic condition using local natural resources, e.g. water and materials and as much as possible using energy efficient systems and components fed by renewables. However, technologies are often imported without any consideration of whether they are adapted to the location. Moreover, affordable energy from fossil fuels make other solutions seem highly expensive and non-competitive.

On the other hand, Arbabian and Sarmadi (2004) suggest that the use of sustainable technologies need to be maximized. One major recommendation for increasing construction production is the use of industrial construction systems. Changes are indeed essential, if the

industry is to meet the demand for new constructions and buildings can become more sustainable. But it can be a serious mistake to assume that a change from traditional to modern imported technology is necessarily the only way of meeting these aims.

Contemporary construction practices that could be adopted in Iran are presented in Table 1. Prefabricated systems with reduced construction time onsite can have an impact reducing emissions in the atmosphere and minimising the impact on the neighbourhood e.g. noise, air pollution and traffic flow. They also reduce requirements to store construction materials on site to a minimum. This is particularly important in populated city centres. Construction systems such as Light steel frame (LSF) are mentioned by Fallah, M. H. (2002) for its sustainability characteristics, but its reduced thermal mass capacity may have a negative impact in the energy use for systems and the moderation of indoor operative temperatures. Table 1 presents the characteristics and advantages of some of industrialized systems from sustainability aspect (Golabchi, M, Mazaherian, H., 2010).

Table 1. Environmental advantages of some of industrialized building systems (Golabchi, M, Mazaherian, H., 2010)

System	Environmental characteristics
Prefabricated concrete system	High structural life service.
	Not using harmful materials for environment as raw materials during construction (Except cement).
	Reduction of construction waste in production stage.
3D panels system	Reduction waste of materials.
	Reduction of energy loss in the environment.
Reinforced concrete system with durable insulated frame	Waste reduction.
	Reduction of gas production and fuel consumption in production stage in comparison with other common systems.
	Reduction of energy loss and good distribution of energy in the environment.
Continuous concrete frames system	Reduction of environmental pollution of this construction method.
	Not using harmful and dangerous materials for environment (Except cement) and the lack of adverse effects of environment.
	Structural life service.

### Case study characteristics

The case study represents a typical residential building in the city centre of Tehran. The building has 5 floors and every floor has 2 residential units with a gross area of around 100m<sup>2</sup> each (88m<sup>2</sup> and 82m<sup>2</sup> useful area in the thermal model). The total building area is 914m<sup>2</sup>.

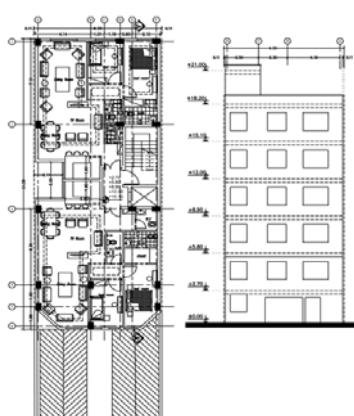


Figure 4. Section

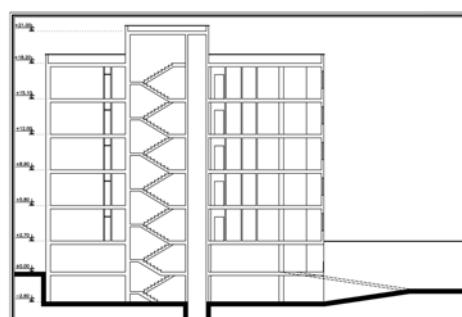


Figure 5. Plan (north up) & North Elevation

Energy modelling was carried out for two cases, using EnergyPlus v.8.6. The first scenario is based on current standard practices in the residential industry.

The second scenario includes a set of variables for improved performance. Sustainable elements have been implemented in the model to increase energy efficiency whilst minimising the environmental impact. The sustainable strategies were selected to be adapted for the climatic conditions, for ease of construction and as low cost as possible. An exception is the use of solar thermal panels for domestic hot water, to promote the use of renewables and the dissemination of low carbon technologies.

Each dwelling is modelled as one single zone. The occupancy density is set as 3 people (99 W/person) with a full occupancy schedule at night (18.00 – 09.00) and half occupied during the day (09.00 – 18.00). Equipment and lights power densities are set as 3 W/m<sup>2</sup>, for a typical domestic occupancy schedule. The heating set point is 20°C and the cooling set point is 24°C. The building circulation is defined as one zone without loads from people or equipment, with 1W/m<sup>2</sup> lights powers density and is fully acclimatised for heating and cooling.

External walls of the standard building are modelled as simple brickwork (260 mm) walls with dense plaster (13 mm). The U-value is 1.3 W/m<sup>2</sup>K. This reference was obtained from the current Building and Regulation of the Iran. The roof is modelled as traditional clay tiles (25 mm), air gap (10 mm) and simple roofing felt (5 mm). Ground floor is modelled as 100 mm cast concrete, 70 mm floor screed and 3 mm timber flooring.

The external walls for the improved scenario are modelled with 2 leaf brickwork (105mm) with 5 cm stone wool insulation and 13 mm plaster. The roof is modelled with typical clay tiles with 18 cm of stone wool insulation. Ground floor is modelled with 100 mm insulation foam, 100mm cast concrete, 70 mm floor screed and 30 mm timber flooring. Triple glazed windows (13 mm air, 6 mm clear glass and glass film) are used for best thermal insulation and the solar heat gain coefficient of the glass is lower than 40% to reduce the excess heat gain from the sun, important in summer. The thermal properties of the building envelope are presented in Table 2.

HVAC is designed according to common residential practices in the region. Heating is provided by a central boiler which works with natural gas. Cooling is provided by a packaged air conditioner unit. Natural ventilation is implemented so no energy is consumed for ventilation. Domestic water heating is provided by electrical heaters for the standard scenario and with solar thermal panels for the improved one.

Table 2. Properties Comparison

	<b>Standard model</b>	<b>Improved model</b>
Building elements (W/m <sup>2</sup> K)	Conventional Envelope Roof: 0.39 External Wall: 1.3 Ground Floor: 0.69 Windows: 1.96 SHGC: 0.69	Improved Insulation Roof: 0.21 External Wall: 0.25 Ground Floor: 0.38 Windows: 1.20 SHGC: 0.36
HVAC	Conventional Equipment Chiller: COP 2.70 Boiler: 80% Pump: 60%	High Performance Equipment Chiller: COP 3.89 Boiler: 100% Pump: 80%
Solar Panels	None	175 m <sup>2</sup> of Solar Panels
Lighting	Incandescent Lighting Residential: 15 W/m <sup>2</sup> Circulation: 6 W/m <sup>2</sup>	LED Lighting Residential: 3 W/m <sup>2</sup> Circulation: 1 W/m <sup>2</sup>

Better mechanical equipment is selected to improve the efficiency. New packaged cooling units can have efficiency rates (COP) up to 3.89 where the standard units have an efficiency of 2.7. Evaporative boilers for heating purposes have efficiency rates of 100%. The efficiency rates of the mechanical equipment are given in Table 2.

Lighting Emitting Diode (LED) lighting is implemented instead of conventional incandescent lamps. LED lamps are almost ten times more efficient than incandescent lamps and their life span exceeds all other lamps.

### **Solar Panels for Domestic Water Heating**

The climate of Tehran is suitable for the use of solar energy for domestic water heating in a residential building. As presented in Figure 3 the energy consumption attributed to DWH has a large impact in the building sector. Thus, solar panels with a total area of 175 m<sup>2</sup> have been designed on the building roof to provide hot domestic water. A total of 35 solar panels was simulated in the new model. Solar panels create a minimum of 220 kWh/day of energy in December and 445 kWh/day of energy in August, which is sufficient to supply all the hot water need for the domestic water usage.

### **Results and discussion**

Table 3 present a detailed energy distribution for the different uses for the whole building. The energy use for lighting has a significant reduction, though this may not be representative for some buildings, as the power density of 15W/m<sup>2</sup> can be considered high. This may have also had an impact in the increase of the heating load. Cooling has a significant reduction of 65% due to a more efficient cooling system and improved envelope with the introduction of shading. The introduction of solar panel for DHW has the biggest effect on the reduction in fossil fuel energy. Equipment loads remain constant on both models. Fans and pumps do not consume much energy and therefore have a minimal impact the total result.

Table 3. Detailed annual consumption for the whole building

	Standard Model (kWh)	Improved Model (kWh)	Percentage Savings (%)
Heating	18179	21435	-17,9%
Cooling	27185	9760	65%
Interior Lighting	39150	7597	81%
Receptacle Loads	6379	6379	0%
Fans	4978	3424	32%
Pumps	126	76	40%
Domestic Water Heating	21855	0	100%
Total	117,852	48,671	59%

The increase of annual heating consumption, despite the use of a more efficient boiler is associated with the new lights. LED lighting emits 90% less heat to its environment than traditional lighting. Thus, the heat gain from lighting is reduced resulting in higher heating loads. Conversely, LED lighting result in a reduction in cooling loads. The upgrade of the opaque envelope and glazing have also had a dual impact in the improved solution. Low U-values will reduce the heat losses in winter, but prevent dissipation of cooling already trapped. Likewise, lower solar transmission will reduce the solar gains in summer but will

prevent useful gains in winter. Lower visible transmittance will also reduce the daylight levels which may increase the need of artificial lighting.

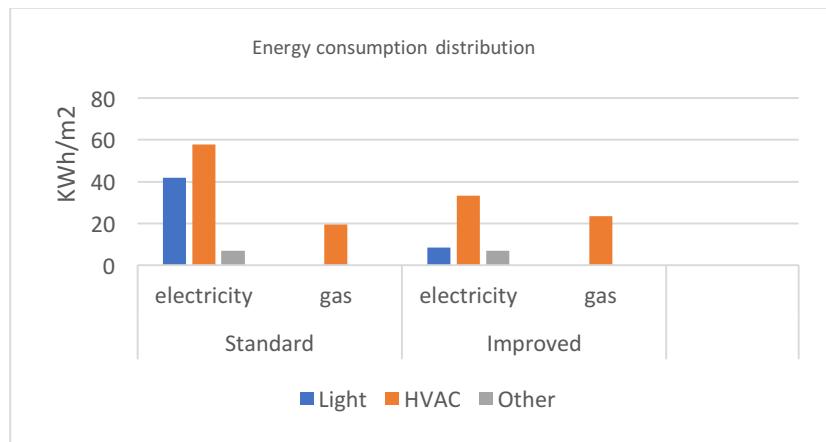


Figure 6. Energy consumption for lighting, acclimatised systems (heating and cooling) and other equipment for the standard and improved scenarios.

Figure 6 shows a comparison of the energy use per meter square to allow unitless comparison with other buildings. It also highlights that electricity has a higher energy usage than gas (exclusive for heating).

Figure 7 highlights a significant reduction on the energy from the standard building (126 kWh/m<sup>2</sup>) to the improved model (kWh/m<sup>2</sup>). This is comparable to standards of good practice in the region.

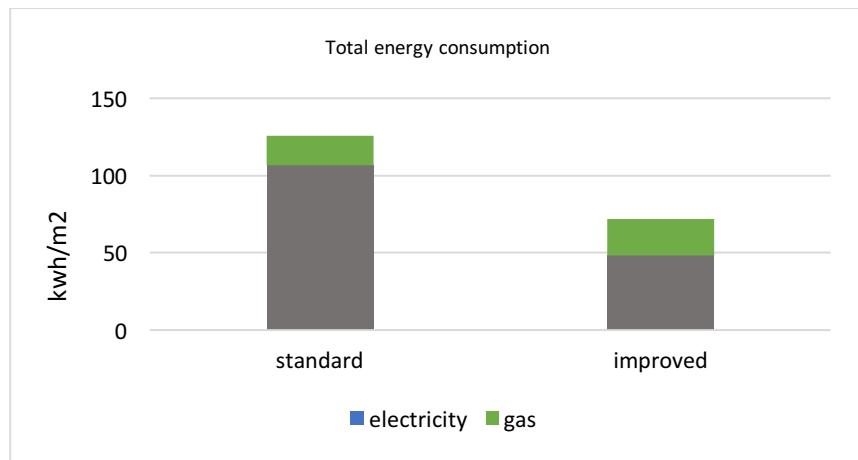


Figure 7. Total energy consumption for the two simulated models.

## Conclusions

Buildings currently pose an ecological challenge greater than any other industry. There is an imperative need to adopt more sustainable practices to reduce CO<sub>2</sub> emissions and promote resilience to cope with climatic events in the future. Despite having vast energy resources derived from fossil fuels, which result in affordable units of electrical and gas used in acclimatising buildings, there is an increasing awareness in Iran of the need to adopt more environmental friendly solutions. There is also the problem of frequent blackouts, due to overload capacity, which puts occupants of buildings heavily reliant of active systems at risk. Climate change and rising temperatures are also aggravating problems of overheating and creating high rates of mortality in heat waves.

Two buildings were compared in this paper: a conventional with the standard practices and an Improved building with sustainable strategies. The sustainable strategies were selected based on literature from other studies, adapted to the climatic conditions and practical and low cost as possible. The results show that it is realistic to design an energy efficient sustainable building.

Overall, adopted sustainable strategies result in 59% annual energy savings. The most important solutions to achieve this saving are: cooling provided by high efficient cooling units, lighting with LEDs and domestic hot water supplied by solar panels.

All in all, the building with sustainable strategies achieved energy savings of 69,000 kWh/year.

## References

- Aghili, J.. (2001). Urban planning and municipal structures: Tehran, Iran. ISBN: 964+5693-28-4 .
- Amanda Heal et al. (2006). The Vernacular as a Model for Sustainable Design .
- Arman Hashemi et al. (2015). Feasibility of Application of Modern Methods of Construction in Iran . International Conference, 22-25 September 2015, Lecce, Italy. .
- Asheim, B. et al. (2007). Constructing knowledge based regional advantage: implications for regional innovation policy. International Journal of Entrepreneurship and Innovation Management .
- Azizi, M. M. et al. (1995). The provision of urban infrastructure in Iran: an empirical evaluation. . Urban Studies, 32(3), pp 507-522.
- Bainbridge, D.A. (2004). Sustainable building as appropriate technology. Sustainable Construction for the Global Village.
- Bartke, R. W. (1973). Land Use Planning in Iran-A Critical Survey. . Wayne Literature Review, pp 20-87 .
- Brockhoff, M. & Brennan, E. (1998). The poverty of cities in developing regions. Population and development Review, pp 75-114 .
- Ermolli (2002). The environmental benefits of the OffSite Manufacturing. CIB World Conference.
- EPO (2010) Energy Balance 2008, Energy planning office, Ministry of Energy: Tehran, pp. 303.
- Fallah, M. H. (2002). Building industry and sustainable development. Soffe magazine(40), pp 64-79.
- Golabchi, M, Mazaherian, H. (2010). Constructional new technologies. . Tehran university publication, Iran.
- Green Building and Design. (2012). Unsustainable Building Practices in Iran.
- H. Arbabian and N.B. Sarmadi. (2004). Improvement of Iranian construction industry.
- Hossein Zabihi et al. (2013). Towards Green Building:Sustainability Approach in Building Industrialization. International Journal of Architecture and Urban Development.
- Kamar, K. A. M. et al. (2010). Sustainable and Green Construction, Construction Industry. Development Board (CIDB) Malaysia.
- Lane, M. B. (2005). Public Participation in Planning: An Intellectual History.
- Ning, C., and Hoon, D. (2011). The sustainable development strategy of tourism resources. Exploring the feasibility for Weihai City of China. International Journal of Procedia Engineering, 21, pp 543-552..
- Peter O. Akadiri et al. (2012). Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. Buildings 2, 126-152.
- Rover, R. (2010). The role of policies in promoting sustainable practices. The Netherlands .
- Shahraki, A. A. (2014). Sustainable new towns in Tehran. Royal Institute of Technology, Stockholm.
- Ujjawal V Sidhpura et al. (2013 ). Major Aspects of Sustainability in Building,Volume : 3 | Issue : 12 | ISSN - 2249-555X.
- van de Ven, F. et al. (2000). Different approaches to assessment of design and management of sustainable urban water systems.



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## Enriching Building Information Modeling (BIM) with Sensor Data and Thermal Images for Thermal Comfort Analysis

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**Abstract:** The lack of adequate data containers and data collection procedures prevents Building Information Modeling (BIM) from being efficiently used for the thermal comfort analysis. The paper presents a framework for integrating environmental data with the BIM for the purpose of thermal comfort analysis. The environmental data, such as indoor/outdoor air temperature, humidity, and temperature values of building envelope collected by measurement instruments and sensors are proposed to be systematically stored in a BIM. In our proposed method, the 3D BIM is enriched by spatio-temporal surface and air temperature information using tools such as Grasshopper visual scripting. The information is used to calculate variables, such as Mean Radiant Temperature (MRT) and operative temperature, to evaluate the occupants' thermal comfort level for each space. The result of the case study verified that the developed system is capable of automatically calculating operative temperature and MRT considering the position of the occupant in the room for assessing the thermal comfort level.

**Keywords:** Building Information Modeling (BIM), thermal comfort, 3D thermal model, temperature sensor, thermographic data, Mean Radiant Temperature (MRT), operative temperature

### Introduction

Thermal performance of the building envelope exerts considerable influence on maintaining indoor environmental conditions. Improving the thermal performance of the building envelope is one of the most effective ways to prevent excessive building energy consumption and to maintain optimal comfortable temperature for occupants. Various sensors are available to capture real-time information that is necessary for building operation and maintenance, e.g., room temperature, humidity level, air flow rate, CO<sub>2</sub> level, and infrared images. Infrared (IR) thermography or thermal imaging and sensors are tools that assist with the diagnosis of building issues, recognizing its problems, prioritizing building maintenance, inspecting hidden problems, and predicting required maintenance.

Building Information Modeling (BIM) has been used for verifying building thermal performance to achieve a higher level of thermal comfort (Sinha et al., 2013). Although BIM provides the ability to share multi-disciplinary information, the current BIM is not yet mature to be readily used for integrating thermal and environmental sensor information to assess thermal comfort. BIM requires tools to extend its ability to analyse the thermal comfort of designed buildings by accommodating environmental information to be used in the analysis process.

This paper presents a methodology for integrating BIM geometry data, thermographic images, and sensing data to calculate thermal comfort level in real-time for each location. The proposed system uses thermographic images that are acquired by a thermal camera and indoor/outdoor air temperatures, which are collected by sensors. The acquired data is integrated with a BIM model using Rhinoceros, which is a BIM compatible software and its visual programming language Grasshopper. The method proposes enriching BIM with sensor data and thermographic images, which can be extracted to calculate operative temperature and mean radiant temperature, considering the angle factor of the occupant's positions in the room for assessing thermal comfort. The main contribution of the paper is to create a novel method and a prototype system to facilitate the assessment of thermal comfort condition in the building using BIM-based environment data. The applicability of the method is verified in a real-world case study.

### Infrared (IR) Thermography

IR thermography has proved to be an adequate technique in measuring surface temperature in a continuous way (Lagüela et al., 2012). However, thermal cameras measure only surface radiation rather than the actual temperature. The surface temperature readings by a thermographic camera show the values for the *apparent temperature* of the targets surface (Rao et al., 2008). According to Stefan–Boltzmann's law, it is possible to convert apparent temperature to the accurate surface temperature by using the following equation (Danese et al., 2010; Ganem et al., 2016):

$$E = \varepsilon\sigma T^4 \quad (1)$$

where  $E$  is the radiation emitted per unit surface ( $\text{W/m}^2$ ),  $\varepsilon$  is the total hemispherical emissivity of the surface ( $0 < \varepsilon < 1$ ) (non-dimensional),  $\sigma$  is the Stefan-Boltzmann's constant ( $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ ) and  $T$  is the surface absolute temperature (K). Usamentiaga et al. (2014) and Revel et al., (2014) proposed to use Equation (2) to calculate a more accurate surface temperature from infrared thermography:

$$T_{obj} = \sqrt[2]{\frac{W_{tot} - (1 - \varepsilon_{obj}) \cdot \tau_{atm} \cdot \sigma \cdot (T_{refl})^4 - (1 - \tau_{atm}) \cdot \sigma \cdot (T_{atm})^4}{\varepsilon_{obj} \cdot \tau_{atm} \cdot \sigma}} \quad (2)$$

$$\text{where } W_{tot} = \varepsilon_{obj} \cdot \tau_{atm} \cdot \sigma \cdot (T_{obj})^4 + (1 - \varepsilon_{obj}) \cdot \tau_{atm} \cdot \sigma \cdot (T_{refl})^4 + (1 - \tau_{atm}) \cdot \sigma \cdot (T_{atm})^4$$

$\varepsilon_{obj}$  is the average emissivity of the surface,  $\tau_{atm}$  is the transmission coefficient of the atmosphere (assumed as a constant value of 0.99),  $T_{obj}$  is the temperature of the target object measured by the IR sensor,  $T_{ref}$  is the reflected temperature, and  $T_{atm}$  is the temperature of the atmosphere (indoor air temperature).

### Environmental Sensors and BIM

BIM offers a basis for sharing the key information about the building that can be used for the analysis of its performance. There is an increasing interest in using BIM not only for design and construction, but also for building operation and maintenance. As well, there is discussion of integrating BIM and sensing data in order to monitor the condition of a building. Ham et al. (2014) stated that the recent BIM-based building energy analysis still deviates from actual measurements as the simulation process purely relies on the information derived from the BIM database without considering the deterioration of building materials. To remove the integration barrier between the actual data and the semantic building data in BIM, a tool that can connect the BIM database with actual data collection should be developed for an efficient analysis of the performance of buildings. Efforts are made to integrate the environmental

sensor data (e.g., temperature, lighting, infrared, noise, humidity, and CO<sub>2</sub>) with BIM for different proposes, such as building energy management by providing the feedback of power usage (e.g., Wang et al., 2013), design development (e.g., Kensek et al., 2013), and the analysis of the thermal performance of building envelope (e.g., Natephra et al., 2016). However, methods for facilitating the calculation of thermal comfort variables by integrating thermography images and temperature sensor data with the BIM database have not been fully proposed to date. Creating such an integrated model still remains as research gaps. Therefore, this research proposes to create new possibilities of using BIM to address the above-mentioned gap.

### **Thermal Comfort Assessment**

Thermal comfort measurable influential factors can be divided into physical, physiological, and psychological factors. One of the most difficult parameters to be analyzed is the Mean Radiant Temperature (MRT) (La Gennusa et al., 2005). Evaluating MRT should take into account not only the thermal radiation coming from surfaces (i.e., walls, windows) but also the thermal radiation hitting the human body from high-intensity sources (La Gennusa et al., 2005). The MRT is defined as the uniform surface temperature of the surrounding walls and surfaces of enclosure that affect the rate of radiant heat loss from the human body. Manual calculation methods to derive MRT ( $T_{mrt}$ ) is complicated and is not suitable for practical usage since the angle factors which weight the influence of surrounding surfaces are difficult to determine (Zmrhal et al., 2003). To calculate MRT by considering the conical angles of building surfaces with respect to the position of human body in a room, three-dimensional calculation should be performed using the following equation (ISO 7726, 1998):

$$T^4_{mrt} = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots + T_i^4 F_{p-i} + \cdots T_N^4 F_{p-N} \quad (3)$$

where  $T_i$  is the average of the surrounding surfaces temperature and  $F_{p-N}$  is the angle factor between the person and surrounding surfaces.

The angle factor between the person and the surface can be computed using the following equation:  $F_{p-i} = F_{\max} [1 - e^{-(a/c)/\tau}] [1 - e^{-(b/c)/\gamma}]$  (4)

where  $\tau = A + B(a/c)$ ,  $\gamma = C + D(b/c) + E(a/c)$

$a$  is the width of the surface,  $b$  is the height of the surface, and  $c$  is the distance between the person and the target surface. Additionally, the radiant heat of each surface in the room is important to combine with the air temperature in order to produce operative temperature, which is defined as a uniform temperature of an imaginary black enclosure in which a person would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment.

### **Visual Programming**

Visual programming interface can replace the conventional coding tools with the visual metaphor of connecting small blocks of independent functionality into a whole system or procedure (Boeykens et al., 2009). An integrated visual programming interface with the existing BIM can easily establish relationships between parameter of building elements and any external data through node-based visual programming language. Additionally, a visual programming interface can provide a new workflow to make the building performance optimization more accessible for innovative energy-efficient building design (Rahmani Asl et al., 2015).

## Proposed System

The proposed system uses visual programming to connect BIM geometric information with sensor data (i.e., air temperature and thermal textures). It consists of five main steps as shown in Figure 1.

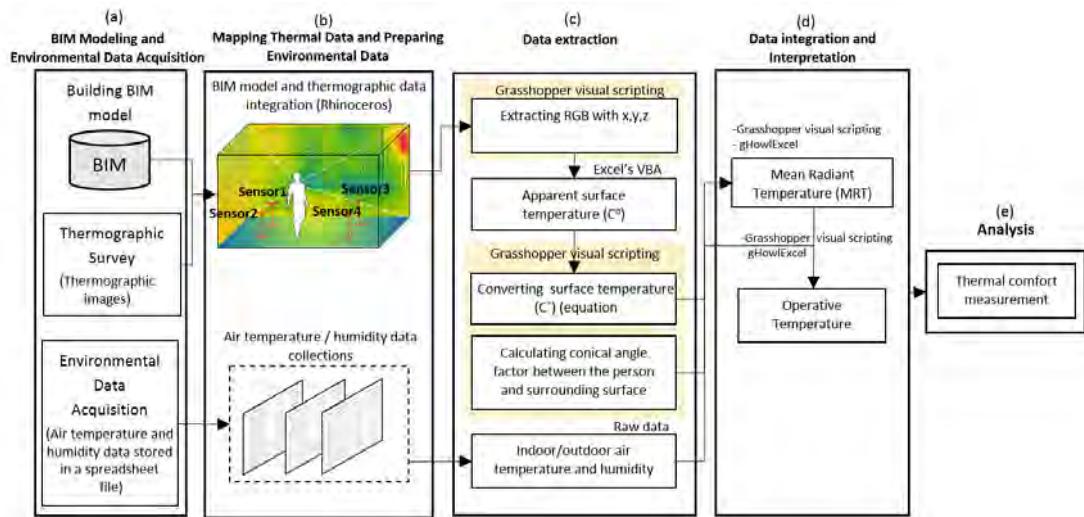


Figure 1. Overview of the proposed method

### BIM Modeling and Environmental Data Acquisition

The first step is BIM modeling and data collection. Thermographic data, including surface temperature readings (i.e., thermographic images) and sensors' readings, including air temperature and humidity values, are collected in a building. A 3D BIM model of the building is also created (Figure 1a).

### Mapping Thermal Data on BIM Model and Preparing Environmental Data

The second step is to map thermographic images on the BIM model and to prepare the acquired environmental data (Figure 1b). In order to integrate thermographic images of the building envelope with the 3D BIM model, Grasshopper visual scripting is used. A series of thermal images are loaded and displayed on the 3D model using the ImageSampler component in Grasshopper. Additionally, in order to add the collected environmental data, such as sensor readings, to the proposed system, a visual programming interface is used. Sensor readings from data logger software, i.e. HOBO Ware, which contains air temperature values, coordinates of sensors, and timestamps, are transferred and stored in spreadsheet data files. The spreadsheet files can be connected with Grasshopper using file path functions and its plug-in gHowl. Consequently, the prototype system produces an enriched BIM model with thermographic textures and with color codes, coordinate references, and the environment sensor data that can be directly read in our system.

### Data Extraction and Data Processing

The third step is data extraction and data processing. The obtained raw data are processed to support thermal comfort evaluation (Figure 1c). In order to acquire the surface temperature data from thermographic images that are mapped on the BIM model in Rhinoceros, visual scripting is used. It extracts numeric RGB values from images and their coordinates positions (x,y,z) (Figure 2a). The RGB values are extracted based on a planar grid of pixels that contains temperature data. The RGB values of the point in the center of each grid is used for the

calculation (Figure 2b), while the size of the grid can be adjusted to suit the requirement of the user. The RGB values are translated to temperature values using a Visual Basic Script (Figure 2b) and a color map is needed to interpret temperature values (Figure 2c). Then, the temperature values from RGB conversion are used to compute the surface temperature using Equation (2).

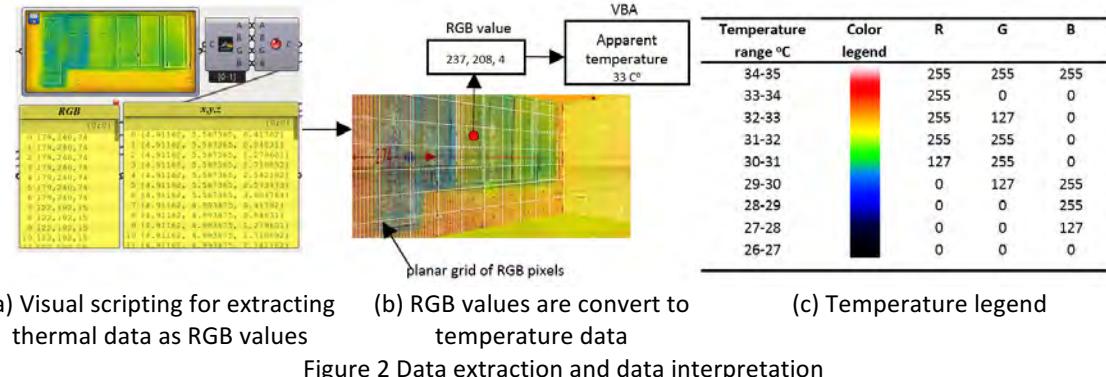
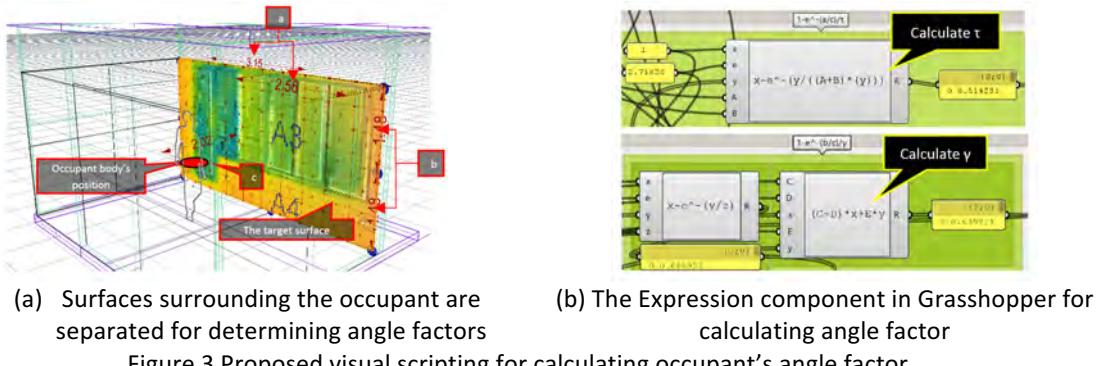


Figure 2 Data extraction and data interpretation

### Calculating Thermal Comfort Variables and Thermal Comfort Evaluation

The fourth step is to create appropriate outputs from the BIM to be used for thermal comfort measurement. In this step, MRT and operative temperature outputs can be obtained (Figure 1d), while in the fifth step, thermal comfort assessment is performed (Figure 1e). To calculate MRT by considering conical angles ( $F_{p-i}$ ) of the building surfaces with respect to the position of the occupant's body, a 3D calculation method is required. Six sides of enclosing surfaces are divided into small surfaces by referencing the occupant's center body position (Figure 3a). Each of these surfaces have their own angle factors and average temperatures. With the help of a visual programming interface,  $a/c$ ,  $b/$ ,  $\tau$  and  $\gamma$ , which are the conical angles ( $F_{p-i}$ ) (explained in Equation (4)), are automatically computed using the expression component in the programming interface (Figure 3b).



After retrieving MRT and the average value of the indoor air temperature, the operative temperature is calculated. In order to evaluate the thermal comfort level based on the adaptive method, Ladybug (a plug-in for Grasshopper (Mostapha et al., 2013)), is used. The adaptive comfort parameters are based on the ASHRAE 55 2013 adaptive standard. The adaptive method model defines comfortable conditions within 80% and 90% acceptability limits (Figure 6b), indicating the percentage of indoor comfort acceptable range.

### Case Study

The student lounge on the 4th floor of the M3 building at Osaka University, Japan, was chosen as an experimentation area (Figure 4a-4b). The case study room is naturally ventilated with

no HVAC system installed and the environmental data collection was executed in the summer (August) in both cloudy and clear weather conditions. The windows in the room were all closed during the experiment. The experimentation room has a typical rectangular shape, as shown in Figure 4c.

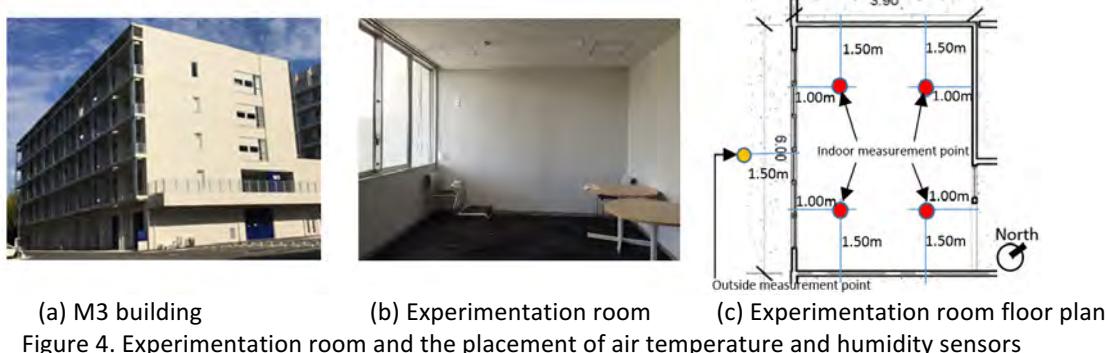


Figure 4. Experimentation room and the placement of air temperature and humidity sensors

## ***3D BIM Modeling and Environmental Data Acquisition***

A 3D BIM model of an existing building is created using Autodesk Revit. The geometry of building elements, e.g., walls, ceiling, windows, doors, and their material properties, are modeled. The model data is then exported to Rhinoceros with Grasshopper scripting via an IFC file.

2D thermographic images were captured using a low cost thermographic camera (i.e., FLIR C2) with infrared sensor 80×60 (4,800 measurement pixels). The temperature range of the camera is  $-10^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$  with a  $\pm 2^{\circ}\text{C}$  accuracy with the field of  $41^{\circ} \times 30^{\circ}$ . The interior thermographic images were captured in cloudy and clear weather conditions, while air temperature and relative humidity data were collected using data loggers (i.e., HOBO UX100, temperature sensor  $\pm 0.21^{\circ}\text{C}$  at  $50^{\circ}\text{C}$ , relative humidity  $\pm 2.5\%$  from 10% to 90% RH). There were four measurement points for collecting indoor air temperature and relative humidity data, and one data collection point was chosen for the outdoor air temperature. The measurement points were chosen at working-level height, approximately 1.0 meter above the floor, with 1.0 and 1.5 meter distances from their adjacent walls. Sensors were set to collect real-time temperature and humidity measurements at time intervals of 15 minutes and the location of each sensor in the experiment room is shown in Figure 4c.

## **Integrating Thermographic Images and Temperature Data with BIM**

The model was exported from Revit to Rhinoceros and then each thermographic image was mapped on its respective parallel wall on the 3D BIM model. Automatic mapping of the thermographic images was performed in Rhinoceros via Grasshopper. Sensor data that are stored in a spreadsheet data file are directly read in the system when calculations of thermal comfort variables are required.

## **Calculating Thermal Comfort Variables**

Two locations in the model were chosen for calculating the MRT, operative temperature, and evaluating thermal comfort during the working hours (from 9 a.m. to 8 p.m.). The BIM model of the experimentation room ( $6\text{m} \times 3.90\text{m} \times 3.2\text{m}$ ) with windows ( $4.80\text{m} \times 2.00\text{m}$ ) is shown in Figure 5.

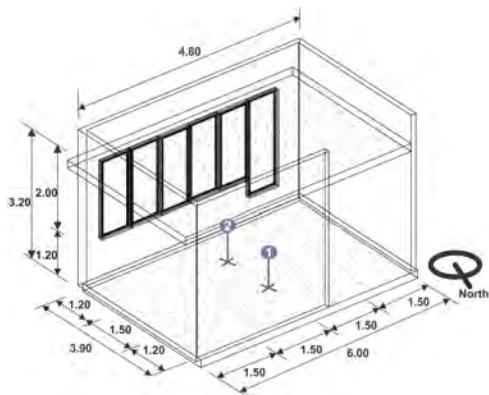
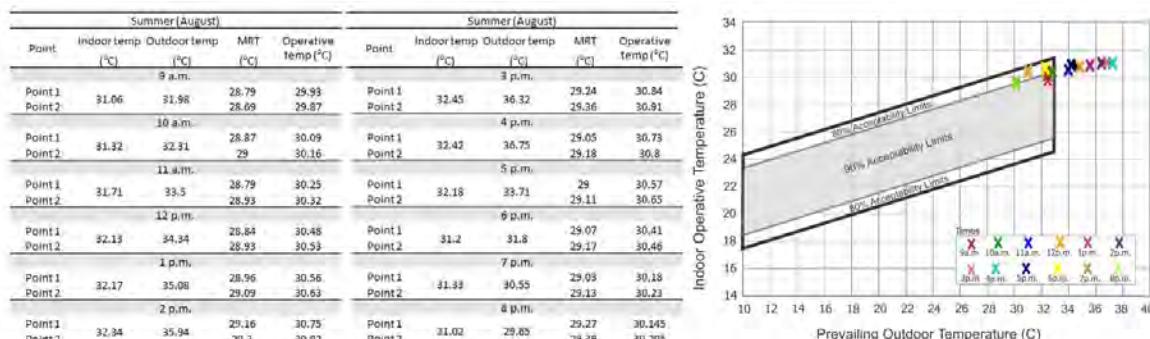


Figure 5. The locations of the assessment points

The average correct surface temperature of each wall is extracted from the thermal model and is converted to the actual surface temperature. These converted surface temperatures are used as input data for calculating MRT and the operative temperature. The values of MRT, considering the occupant position and operative temperature, are computed using the proposed visual scripting and the results are reported in Figure 6a.

In order to assess indoor thermal comfort conditions, the adaptive chart is used. Figure 6b shows that in the morning from 9 a.m. to 10 a.m., the thermal comfort condition complies with the ASHRAE standard (90% acceptable limits), while from 11 a.m. to 5 p.m., the thermal condition is uncomfortable, the room feeling too hot for occupants. The poorest thermal conditions occurred in the afternoon between 3 and 4 p.m. During this time, indoor temperature, outdoor temperature, MRT, and operative temperature are reached 32.45°C, 36.75°C, 29.29°C, and 30.74°C, respectively. ASHRAE standards recommend a comfortable temperature between approximately 23°C – 28°C in the summer. In consequence, the reduction of operative temperature and MRT from approximately 5°C to 6°C can help to maintain thermal comfort during this time.



(a) Observed indoor/outdoor air temperature measurement and calculated value of MRT and operative temperature considering angle factors of two occupant locations

Figure 6. Values for thermal comfort variables and the measurement of thermal comfort

## Conclusions

This paper investigated a method for enriching BIM with thermal information that can be used for the indoor thermal comfort evaluation of buildings. A BIM compatible application (Rhinoceros and its plug-in Grasshopper) was chosen for the development of the system. The proposed method has been verified in a student lounge of Osaka University building. With the help of visual scripting, thermal textures, sensor data, and the BIM model, this can be successfully integrated. In addition, our system facilitated the process of calculating MRT

considering the corresponding angle factors. Furthermore, it provides an easy way to examine thermal comfort conditions of the buildings and to identify potential problems, which helps to achieve a higher degree of satisfaction in terms of thermal comfort for occupants. Future studies will include extending the capability of our system in order to evaluate indoor thermal comfort in air-conditioned buildings, using the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) methods, as well as investigating a method to fully automate the construction of a thermal 3D model using photogrammetry.

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## References

- Boeykens, S. & Neuckermans, H., 2009. Visual programming in architecture: should architects be trained as programmers?. In: *Joining Languages Cultures and Visions: CAADFutures 2009*, Montréal, Canada.
- Danese, M. Demsar, U. Masini, N. & Charlton, M., 2010. Investigating material decay of historic buildings using visual analytics with multi-temporal infrared thermographic data. *Archaeometry*, 52(3), pp.482-501.
- Ganem, C. Barea, G. Ganem, C. Barea, G. & Balter, J., 2016. Infrared thermography for quick thermal diagnostic of existing building infrared thermography for quick thermal diagnostic of existing building. In: *PLEA 2016*, Los- angeles. USA: PLEA 2016 Los Angeles
- La Gennusa, M. Nucara, A. Rizzo, G & Scaccianoce, G., 2005. The calculation of the mean radiant temperature of a subject exposed to the solar radiation - A generalised algorithm. *Building and Environment*, 40(3), pp.367–375.
- Ham, Y. & Golparvar-Fard, M., 2014. Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction*, 49, pp.214–224.
- ISO 7726. 1998 Thermal environments— instruments for measuring physical quantities. Geneva: International Standard Organization.
- Kensek, K. & Kahn, W., 2013. Integration of environmental sensors with BIM seven case studies. In: *BESS-SB13: Advancing Towards Net Zero*, Pomona. California: Simpson Gumpertz & Heger.
- Lagüela, S. Armesto, J. Arias, P. & Herráez, J., 2012. Automation in construction automation of thermographic 3D modelling through image fusion and image matching techniques. *Automation in Construction*, 27, pp.24–31.
- Lin, Y.H. Liu, Y. S. Gao, G. Han, X. G. Lai, C.Y. & Gu, M., 2013. The IFC-based path planning for 3D indoor spaces. *Advanced Engineering Informatics*, 27(2), pp.189–205.
- Natephra, W. Motamed, A. Yabuki, N. Fukuda, T. & Michikawa, T ., 2016. Building envelope thermal performance analysis using BIM-based 4D thermal information visualization. In: *ICCBCE 2016*, Osaka, Japan.
- Rahmani Asl, M. Zarrinmehr, S. Bergin, M. & Yan, W., 2015. BPOpt: A framework for BIM-based performance optimization. *Energy and Buildings*, 108, pp.401–412.
- Rao, D., 2008. Infrared thermography and its applications in civil engineering. *Indian Concrete Journal*, 82(5), pp.41–50.
- Revel, G.M. Arnesano, M. Pietroni, F. Schmidt, M. & Kaschtschejewa, O., 2014. Evaluation in a controlled environment of a low-cost IR sensor for indoor thermal comfort measurement. In: *QIRT 2014*, Bordeaux, France.
- Sadeghipour, R. M. Pak, M. & Adrian, S., 2013. Ladybug: a parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design. In: *IBPSA*, Chambéry, France.
- Sinha, S. Sawhney, A. Borrman, A. Ritter, F., (2013) Extracting information from building information models for energy code compliance of building envelope. In: *RICS COBRA 2013*, New Delhi India.
- Usamentiaga, R. Venegas, P. Guerediaga, J. Vega, L. Molleda, J & Bulnes, F.G., 2014. Infrared thermography for temperature measurement and non-destructive testing. *Sensors (Basel, Switzerland)*, 14(7), pp.12305–12348.
- Wang, H. Gluhak, A. Meissner, S. & Tafazolli, R., 2013. Integration of BIM and live sensing information to monitor building energy performance. In: *CIB W78*, Beijing. China: Tsinghua University.
- Zmrhal, V., Hensen, J. & Drkal, F., 2003. Modeling and simulation of a room with a radiant cooling ceiling. In: *IBPSA*, Eindhoven, Netherlands, pp. 1491–1496.



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*Design to Thrive*

## Predicting Neutral Temperature and Comfort Range of Traditional Buildings in the Dry Season at Okigwe, Nigeria

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**Abstract:** In the search for comfortable thermal environment, this paper investigated thermal sensations and indoor air temperature of traditional buildings in the dry season at Okigwe, Nigeria, with the aim of developing a model for the prediction of neutral temperature and comfort range. Data were obtained through administration of copies of questionnaires, and measurement of indoor air temperature, monitored simultaneously from 1 November 2015 to 31 March 2016, in the two selected traditional buildings, constituted the field measurement. In addition, monthly repeated transverse survey was conducted to record the thermal sensation votes of the occupants in the monitored buildings. The findings showed that the mean dry season indoor air temperature was  $28.8^{\circ}\text{C}$  with maximum of  $30.5^{\circ}\text{C}$  and minimum of  $27.2^{\circ}\text{C}$ . The mean occupants' thermal sensation votes (TSV) was regressed upon indoor air temperature (MIT) and a prediction model:  $\text{TSV} = 0.65 (\text{MIT}) - 13.5$  was developed, through which the neutral temperature was determined to be  $26.8^{\circ}\text{C}$  and comfort range between  $25.6^{\circ}\text{C}$  and  $28.2^{\circ}\text{C}$ . Thus, the model developed could be used, prior to the conceptualisation of design ideas, for the prediction of thermal sensations of the occupants of traditional buildings in the dry season at Okigwe, a warm climatic zone in Nigeria.

**Keywords:** Dry season, Neutral temperature, Indoor thermal comfort, Traditional buildings and Thermal sensation

### Introduction

In buildings, increased productivity, well-being, and overall satisfaction are primarily some of the expectations of occupants as most of their times and activities are spent within them. The search for thermally comfortable environment amidst excessive costs of energy, fossil fuel, and emergent issues from global climate changes have led to the continuous development of mitigation and adaptation strategies and standards. To achieve optimum thermal environment, humankind deploys passive strategies involving use of ambient energy resources and active controls mechanisms concerned with adoption of electro-mechanical devices for comfort. Several organisations in the developed countries, such as American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), European Standards (EN), and International Organisation for Standardisation (ISO) provide standards, codes, and indices that are universally considered for indoor thermal comfort predictions (Djamila, 2014). However, one of the significant issues from these internationalisation is that responses to the prescriptions of the climate vary according to location and people. This Karyono (2015) corroborated in a previous study that differences in subject comfort temperatures were due to bodily adaptation to the surrounding climate.

Nigeria, despite being the most populous country in Africa and seventh in the world, has neither standard energy efficiency code for buildings nor thermal comfort standard

(Efeoma & Uduku, 2016). The fewer studies that have been undertaken on indoor temperature settings in Nigeria, depended more on occupants' preferences. It is not always possible to make thermal comfort, which is that condition of the mind which expresses satisfaction with the thermal environment, satisfy all occupants at the same time. (ASHRAE 55, 2004). This was why Fanger (1972) stated that people are not the same in responding to a given surrounding environment due to inter personal differences. This notwithstanding, there is a comfort temperature at which the human body feels most comfortable: neither hot nor cold (Akande & Adebamowo, 2010).

This paper investigated indoor environmental variable of air temperature and thermal sensations of the occupants of traditional buildings in the dry season at Okigwe, a warm-humid climatic region of Nigeria, with a view of developing a model for the prediction of neutral temperature and comfort range. The dry season is associated with hot temperatures as such demands more energy for cooling. The paper therefore, contributes to discussions on the provision of acceptable indoor thermal environment where energy consumption is minimised for maximum comfort.

### **Neutral Temperature and Comfort Range**

Neutral temperature is defined as the temperature when occupants of a space experience neither warm nor cool; hot nor cold. It is also referred to as thermal neutrality and the indoor operative temperature coinciding with the group's mean thermal sensation of 'neutral' on the 7-point ASHRAE scale (Candido, et al., 2010). In other words, it is the midpoint on ASHRAE's comfort scale '4' or '0' for (1 – 7) or (-3 to +3) respectively. Nicol, et al. (2012) suggests that operative and air temperatures in most indoor conditions are the same. Furthermore, Candido and Lamberts (2010) identified four factors that can be combined to produce differences in neutral temperature for an individual and they comprise thermal environment, level of activity, thermal insulation of the clothing, and physiological state of the individual.

Air temperature as observed by Karyono (2015) is the most common and comparable index to be used in expressing the warmth and coolness of the environment, and it has also been used to investigate comfort temperatures of group of people in many parts of the world. Efeoma and Uduku (2016) summarised the findings of previous studies on thermal comfort in Nigeria, with information on locations, climatic zones, types of buildings, and seasons. Other data given were the neutral temperatures, regression lines and acceptable comfort ranges. The study was on adaptive thermal comfort of office workers in the hot-humid climate of Enugu, Nigeria, in both dry and rainy seasons. A regression line of  $Y = 0.250*X - 7.197$ , neutral temperature of  $28.8^{\circ}\text{C}$ , comfort range of (TSENS – Thermal Sensations – between -0.85 and to +0.85) of between  $25.4^{\circ}\text{C}$  and  $32.2^{\circ}\text{C}$ , and combined mean indoor air temperature of  $28.5^{\circ}\text{C}$  were established. Despite several studies on thermal comfort in Nigeria, there is paucity of research findings on thermal comfort conditions of traditional buildings.

### **The Study Area**

Okigwe, a semi-urban city in the warm-humid climate of Nigeria, it lies between Latitudes  $5^{\circ} 30'$  and  $5^{\circ} 57'$  North of the Equator and Longitudes  $7^{\circ} 04'$  and  $7^{\circ} 26'$  East of the Greenwich Meridian. It is in the tropical rainforest climate designated as 'AF' by the Koppen climate classification. The maximum and minimum annual temperatures are  $27.6^{\circ}\text{C}$  and  $25.0^{\circ}\text{C}$  respectively with a range of  $2.6^{\circ}\text{C}$ . The mean annual temperature is  $26.4^{\circ}\text{C}$ . The city experiences dry and rainy seasons with 2333 mm annual rainfall. The dry season is

accompanied by a dust-laden wind from the Sahara Desert, known as Harmattan, which is brought by the Tropical Continental (cT) air mass, while the rainy season is heavily influenced by the Tropical Maritime (mT) from the Atlantic Ocean. It is made up of twenty-two autonomous communities with eleven electoral wards as recognised by the Nigerian Independent National Electoral Commission (INEC) wards.

## **Methodology**

This paper reports the investigation of thermal sensation votes of occupants and indoor air temperature of traditional buildings from a parent study on: Comparative Evaluation of Indoor Thermal Comfort Conditions of Traditional and Contemporary Buildings in the Dry Season at Okigwe, Nigeria. The parent study aimed at the establishment of design criteria for thermally comfortable environment and the objectives examined thermal design characteristics, thermal sensations of occupants, indoor air temperature and relative humidity values of traditional and contemporary buildings. Survey and field measurement research design approaches was adopted in this study.

Data from survey approach were obtained through self-administrated questionnaires. Self-administered questionnaire as described in Oppenheim (2005) is a technique of data collection, whereby the questionnaires are usually presented to the respondents by an interviewer or approved representative. In this study, research assistants trained in the local milieu of the study area assisted in the distribution of copies of the questionnaires. They interpreted the questionnaire contents in the local dialect as most of the occupants of traditional buildings are illiterates. Indoor air temperature monitored simultaneously in two traditional buildings constituted the field measurement data. In addition, repeated transverse survey was conducted to obtain monthly thermal sensation votes of the occupants of the selected traditional buildings. Repeated transverse survey as described in Nicol et al. (2012) is an approach where the same population is visited periodically to collect data, say once a month or once a season. The respondents in the sampled traditional buildings were visited once a month from November 2015 to March 2016 to record their thermal sensation votes and same period was used to collect data on the indoor air temperature.

## ***Population and Subject Characteristics***

The study was made of two populations: buildings and occupants. Buildings whose fabric: walls, roofs and floors were made of mud, thatch, and rammed earth respectively were chosen as representative samples of traditional buildings. Evans (1980) buttressed the choice of roof and wall as both possess qualities that modify the internal environment of buildings. Two buildings were selected, though one of them had its roof element made of corrugated iron roofing sheets. The occupants' population comprised 150 randomly selected adult household heads who live in buildings whose fabric characteristics represented those of traditional buildings.

## **Data Collection**

In the distribution of the self-administered questionnaires, a two-level multi-stage cluster sampling technique was adopted. The first stage had a sampling frame of the 22 autonomous communities in the study area stratified into the 11 electoral wards as recognised by the INEC. In the second stage, the electoral wards were arranged alphabetically and through random sampling of one out of every two (1:2); however, two wards belong to the same autonomous community (Umulolo) and were merged as one ward for this study, thus giving a total of ten

electoral wards. Five wards were selected: Aku, Amuro, Ogii, Okigwe Urban 1, and Umulolo and copies of the questionnaires were self-administered at the rate of 30 copies per ward. The questionnaires were coded with pre-determined questions meant to elicit responses on the occupants' thermal sensations using the seven-point ASHRAE thermal sensation scale ranging from 'cold' (vote 1) to 'hot' (vote 7). The other variables examined typical characteristics of the respondents and buildings: sex, age of the respondents, length of stay in the buildings and city, and age of the buildings. The materials used for external walls and roof covering sheets were also investigated.

### **Field Experiment**

Indoor environmental variable of air temperature was monitored simultaneously in the two traditional buildings selected from the five electoral wards in the study. Hourly values were recorded for 152 days (1 November 2015 to 31 March 2016) covering the dry season period. The measuring instrument was Tinytag Explorer 4.9 Germini Data Loggers with air temperature range capacity of  $-25^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$ . The measuring instruments were mounted at a height of 1200mm above the finished floor and positioned to avoid direct sunshine and precipitation. One of the traditional buildings (T1) lies between latitude  $5^{\circ} 48' 57'' \text{ N}$  and longitude  $7^{\circ} 18' 45'' \text{ E}$  (Fig 1) and the other (T2) between latitude  $5^{\circ} 49' 16'' \text{ N}$  and longitude  $7^{\circ} 19' 04'' \text{ E}$  (Fig 2).



Fig 1: T1



Fig 2: T2

### **Analysis and Results**

#### ***Demographic Data of the Respondents and Characteristics of Traditional Building Types***

Of the 150 copies of questionnaires administered, 115 were returned, a response rate of 77%. The response rate of 77% is acceptable and it far exceeded the opinion of Akintoye (2000) who reported that the normal response rate for questionnaires should be around 20 – 30 percent. Most (91%) of the respondents were above 30 years of age and have lived more than 30 years both in the buildings and Okigwe city. This made their responses quite reliable. There was not much difference between their sexes; 52 and 48 percent. The traditional buildings under study have been in existence for more than 50 years as greater parts of the materials for the external walls were made of mud. The use of thatch as roof covering element was on the decrease as only 28% of the traditional buildings retained the mud walls and thatch. This implies rejection of the practices of our ancestors in favour of the tenets of contemporary systems as presented in Table 1.

### **Field Experiment and Repeated Transverse Survey**

The monthly mean values obtained from the field measurements of hourly indoor environmental variable of air temperature were recorded and presented in Table 2. The mean monthly minimum air temperature value recorded ranged from as low as  $24.8^{\circ}\text{C}$  in December 2015 to as high as  $28.5^{\circ}\text{C}$  in February 2016. Also, the mean monthly maximum air temperature value recorded ranged from as low as  $29.7^{\circ}\text{C}$  in December 2015 to as high as  $32.7^{\circ}\text{C}$  in February 2016. The average maximum air temperature for the period was  $30.5^{\circ}\text{C}$  recorded in February 2016, and minimum was  $27.2^{\circ}\text{C}$  recorded in December 2015. The mean dry season air temperature was determined to be  $28.8^{\circ}\text{C}$  and standard deviation of  $1.3^{\circ}\text{C}$ . The mean monthly values of the thermal sensations of the occupants of traditional buildings were recorded through a repeated transverse survey and were also reported in Table 2. The occupants felt warm in February 2016 and neither hot nor cold in December 2015. It is to be noted that the maximum indoor air temperature was recorded in February 2016 and minimum in December 2016.

Table 1: Demographic Data of the Respondents and Characteristics of Traditional Buildings

Variables	Value Label	Frequency (N)	Percentage (%)
Age	< 30 years	10	9
	> 30 years	105	91
Duration in the building	< 30 years	33	27
	> 30 years	82	73
Duration in the town	< 30 years	30	26
	> 30 years	85	74
Sex	Male	60	52
	Female	55	48
Age of the Building	< 50 years	19	17
	> 50 years	96	83
Materials for External Wall	Mud	113	98
	Sandcrete Block	2	2
	Brick	0	0
Materials for the Roof covering sheets	Thatch	32	28
	Iron Sheets	83	72
	Aluminium Sheets	0	0

Source: Fieldwork, 2015

### **Thermal Sensation Votes**

The respondents were asked to express their feelings about the thermal conditions in their immediate environment by asking them "how are you feeling now in the building" and their responses were recorded on the seven-point ASHRAE thermal sensation scale ranging from 'cold' (vote 1) to 'hot' (vote 7). From Fig 3, the vote distribution got from the respondents of traditional buildings showed that 47% of the votes were cast inside the ASHRAE thermal comfortable range (vote =3, 4 & 5). The median and mode values were 5, which indicated that the occupants felt slightly warm in the dry season.

Table 2: Mean Values of Thermal Sensation Votes (TSV), Minima and Maxima Indoor Air Temperature values and the Statistical Summary for Traditional Buildings

Period	TSV	Min (°C)	Max (°C)	Average (°C)
November 2015	4.7	26.8	30.2	28.3
December 2015	4.0	24.8	29.7	27.2
January 2016	5.1	26.1	30.8	28.4
February 2016	6.5	28.5	32.7	30.5
March 2016	5.5	27.9	31.5	29.6
Mean				28.8
Minimum				27.2
Maximum				30.5
Standard Deviation				1.3

Source: Fieldwork, 2015

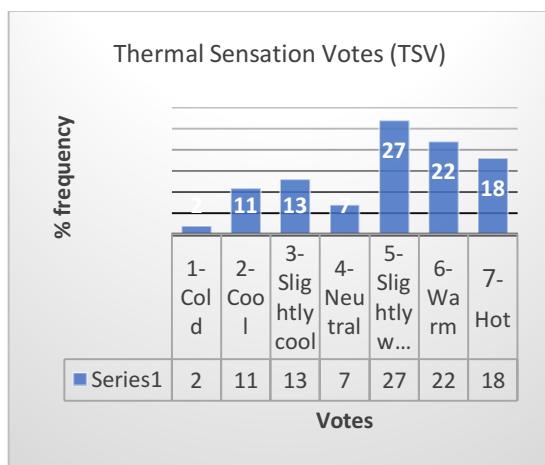


Fig 3: Thermal Sensation Votes

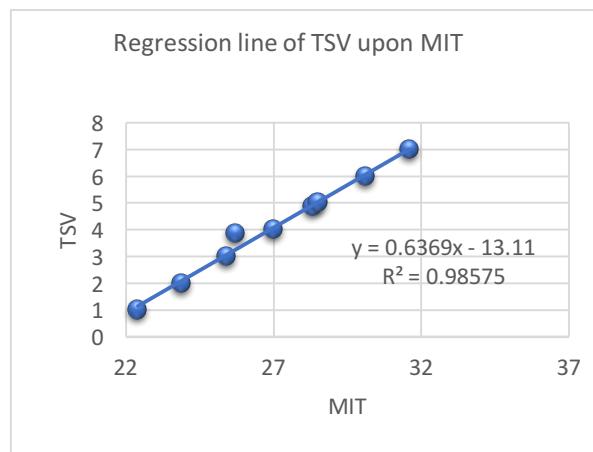


Fig 4: Regression line of TSV on MIT

### Comparison of Thermal Sensation Votes and Indoor Air Temperature

The variation between the values of indoor air temperature (MIT) and mean thermal sensation votes (TSV) of the occupants of traditional building types was significant [ $F(1,3) = 29.74$ ,  $p = 0.012$ ] at 95% confidence level. To predict neutral temperature, the mean thermal sensation votes were regressed upon the mean dry season indoor air temperature values using the MS Excel application. There was a very strong positive relationship ( $r = 0.993$  at  $p < .001$  level of significance) between TSV and MIT, the coefficient of determination ( $R^2$ ) was 0.995, and the regression was significant at 95% confidence level. The predictor variable, MIT explained 65% of the variance of occupants' thermal sensations. Thus, the relationship that connects TSV and MIT was expressed as a linear equation that predicts TSV from MIT. The equation of the regression line (Fig 4) had the form:

$$Y'_1 = a_1 + b_1 X_1 \quad (1)$$

Where  $Y'_1$  is the predicted value (TSV),  $a_1$  = the intercept on the y-axis,  $b_1$  = the regression coefficient and  $X_1$  = the independent variable (MIT). The regression of TSV upon MIT yielded the line that predicted the mean response at each indoor air temperature. The equation of the regression line had the form:

$$TSV = 0.65 (MIT) - 13.5. \quad (2)$$

### **Predicting Neutral Temperature and Comfort Range**

From equation 2, the neutral temperature was determined by substituting  $TSV = 4$  (neutral or comfortable). It yielded a neutral temperature of  $26.8^{\circ}\text{C}$ . The comfort range ( $3.15 \leq TSV \leq 4.85$ ) representing 80% of the votes in the ASHRAE acceptable thermal comfort range (votes = 3, 4 and 5) was determined to be between  $25.6^{\circ}\text{C}$  and  $28.2^{\circ}\text{C}$ .

### **Discussion**

The indoor air temperature of buildings is dependent on the components and composition of the envelope for thermal comfort. Traditional buildings are unique in its form and materials; but the findings from this study indicate a discontinuation trend in the adoption its methods and components, as only a quarter (28%) of the existing buildings still had its full complement. The corrugated iron roofing sheet which is a contemporary building material has replaced the thatches on traditional buildings. The assessment of the subjective comfort votes based on the seven-point ASHRAE scale revealed that the occupants of traditional building were not comfortable with the thermal environment of their buildings as less than half (47%) of the votes were cast inside the central three categories of the thermal sensation scale. The ASHRAE scale recommends that an acceptable comfortable thermal environment should have 80% of occupants' votes in the central three categories of (vote =3, 4 & 5 on 1 to 7 scale).

The relationship between indoor air temperature values and mean values of occupants' thermal sensation votes was found to be significantly different. Indoor air temperature would increase by 65% for a 100% increase in the thermal sensations of the occupants. The neutral temperature ( $26.8^{\circ}\text{C}$ ) and comfort range ( $25.6^{\circ}\text{C} - 28.2^{\circ}\text{C}$ ) established in this study had lower values when compared with other related findings. Efeoma and Uduku (2016) reported a neutral temperature of  $28.5^{\circ}\text{C}$  for both dry and rainy seasons. The study area, Enugu, Nigeria is in the same warm-humid climatic region with Okigwe, Nigeria. This may not be unconnected with differences in the behavioural adaptations, seasons and type of buildings studied.

The lower value obtained is also indicative of the good thermal qualities of traditional buildings. The locally available materials, resources and conditions used in the construction of traditional buildings without recourse to mechanical and artificial systems of heating, ventilation and air conditioning; aided in the reduced values obtained. This implies that the methods and components of traditional buildings lead to reduced consumption of substantial amounts of energy and costs (Roaf, et al., 2009; Qaemi & Heravi, 2012; Sarkar, 2013). Whereas, active control systems promote use of electro-mechanical devices for comfort, which adversely affect the environment by causing mismanagement of energy resources (de Dear & Brager, 1998).

### **Recommendations and Conclusion**

The paper investigated occupants' thermal sensations, and indoor air temperature values of traditional buildings in the dry season, when the cooling load requirement is high, at Okigwe, Nigeria, with the aim of developing model for predicting neutral temperature and comfort range. The relationship between TSV and MIT was significant, which supported the development of the prediction model:  $TSV = 0.65 (\text{MIT}) - 13.5$ . The model developed would predict neutral temperature of traditional buildings at Okigwe, and other areas in the warm-humid climate, within the comfort range of between  $25.6^{\circ}\text{C}$  and  $28.2^{\circ}\text{C}$ . The study agrees that the development of prediction model of comfort temperature of traditional buildings is a step toward evolution of the Nigerian thermal comfort standard, using piecemeal thermal comfort

studies of diverse building types and geographical locations. Also, the study revealed the abandonment of traditional buildings in favour of contemporary building styles even though, traditional buildings are known to have climatically and culturally influenced building design characteristics (Roaf, et al., 2009). This model is recommended for the future evaluation of indoor thermal comfort conditions of traditional buildings in the dry season at Okigwe, Nigeria, by architects, planners, environmental designers, policy makers, and students. It is also recommended that further studies on comfort temperature and range during the rainy season be investigated.

### Acknowledgements

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### References

- Akande, O. K. & Adebamowo, M. A., 2010. *Indoor Thermal Comfort for Residential Buildings in Hot-Dry Climate of Nigeria*. Cumberland Lodge, Windsor, UK, Network for Comfort and Energy Use in Buildings, pp. 1-11.
- Akintoye, A., 2000. Analysis of Factors Influencing Project Cost Estimating Practice. *Construction Management and Economics*, Volume 18, pp. 77-89.
- ASHRAE 55, 2004. *ANSI/ASHRAE Standard 55-2004: Thermal Environment Conditions for Human Occupancy*. Atlanta, Georgia: American Society of Heating, Refrigerating and Air Conditioning Engineers.
- Candido, C., de Dear, R. J., Lamberts, R. & Bittencourt, L., 2010. Air Movement Acceptability Limits and Thermal Comfort in Brazil's Hot Humid Climate Zone. *Building and Environment*, pp. 222-229.
- de Dear, R. & Brager, G. S., 1998. Toward an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions*, 104(1), pp. 145-167.
- Djamila, H., 2014. Exploring the Preferred Temperatures on Occupants Thermal Comfort in the Humid Tropics. *International Journal of Research in Engineering and Technology*, 3(4), pp. 98-102.
- Efeoma, M. & Uduku, O., 2016. *Longitudinal Survey of Adaptive Thermal Comfort of Office Workers in the Hot Humid Zone of Enugu, Nigeria*. Cumberland Lodge, Windsor, UK, Network for Comfort and Energy Use in Buildings.
- Evans, M., 1980. *Housing, Climate and Comfort*. New York: Halsted Press.
- Fanger, P. O., 1972. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. New York: McGraw-Hill.
- Karyono, T. H., 2015. Predicting Comfort Temperature in Indonesia, an Initial Step to Reduce Cooling Energy Consumption. *Buildings 2015*, pp. 802-813.
- Nicol, F., Humphreys, M. & Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice*. London : Routledge.
- Oppenheim, A. N., 2005. *Questionnaire Design, Interviewing and Attitude Measurement*. New ed. London: Continuum.
- Qaemi, M. & Heravi, G., 2012. Sustainable Energy Performance Indicators of Green Building in Developing Countries. *Construction Research Congress*, pp. 1961-1970.
- Roaf, S., Crichton, D. & Nicol, F., 2009. *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide*. Oxford: Elesvier Press.
- Sarkar, A., 2013. Study of Climate Responsive Passive Design Features in Traditional Hill Architecture of Khyah Village in Hamipur, Himachal Pradesh, India for Indoor Thermal Comfort. *J. Inst. Eng. India Ser. A*, 94(1), pp. 59-72.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Opine - Participative model for evaluation of comfort conditions in open urban spaces

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**Abstract:** This article presents a participative model for evaluation in open urban spaces, named Opine. The mobile application was developed for the investigation of user comfort. The application's objective is to verify the users' perception of open urban spaces with regard to thermal environmental conditions; acoustics; daylight and ergonomics, and enable quick acquisition of these opinions. Studies in the area of environmental comfort and climate in open urban spaces presuppose the acquisition of data pertaining to environmental conditions, the physical characterization of spaces and users' opinions (subjective answers). The last years have shown that, despite the technology used in field researches, part of this information could be acquired in a more dynamic manner. The development of the application led us to think of it as merely a questionnaire, for it would – then – be more direct and easy to understand. The application was developed for Android systems, with the following characteristics regarded as Paramount: easy to understand; clear; organized; easy to read. It should also be visually instinctive to the user, making the data acquisition process more agile and also enabling the rapid and dynamic treatment of the data.

**Keywords:** urban space, participative model, environmental comfort, Android system, OPINE.

### Introduction

Quality of urban spaces contributes to quality of life, and knowledge of the relations between urban micro-climatic patterns and their implications to users' environmental comfort is a practical and effective solution. More than 50% of people in the world live in cities and – thus – knowledge of urban climate contributes to the understanding of urban sustainability. Also, when projected with potential global climate changes (PBMC, 2014), urban climate should be contemplated in the parameters for urban planning and qualification of open urban spaces. Urban climate is one of the elements of the physical environment which – although affects health, laboral performance and human psychological state – is frequently neglected in urban planning and design of cities and urban spaces.

Knowledge of the relations between microclimate and user comfort provides tools for large-scale planning and design, enabling a better living for people in urban spaces. According to Mills (2006), had climate studies been incorporated into the zoning of cities, many environmental problems could have been reduced.

Whenever exposed to open urban spaces, users are subjected to large-scale climate conditions and the surrounding built environment. Geometry and density of the urban environment influence the trapping of solar radiation and of long-wave radiation emitted by the surfaces, the reduction of turbulent heat transport and losses to the atmosphere, and the quantity of anthropogenic heat thrown into the atmosphere through engines in general, as per Oke (1987). On the other hand, a surface with vegetation reduces heating in the local space scale through shadowing and attenuation of inciding solar radiation, as well as – and mainly in larger space scales – through evapotranspiration, which minimizes the flow of sensible heat to the air.

These conditions may cause the user to feel comfortable or thermally stressed, particularly in warmer periods of the year – when they result from air temperature and humidity, exposure to solar radiation and radiation exchanges with the surrounding environment. It is clear that natural ventilation conditions, characteristics of garments and the activity engaged in by the pedestrian (walking, running, sitting, etc.) also contribute to a greater or lesser stress experienced by the users while in open urban spaces. Likewise during colder periods. The relations of the climate variables (temperature, humidity, air velocity and thermal radiation), in tandem with the mapping of the urban fabric (physical building characteristics) can aid in the analysis of responses obtained from the users and their respective positioning in the grid of the urban fabric.

Empirical studies are necessary not only for determining specifics of the adaptation and acclimatization characteristics of a population in a given climatic context, but also for the calibration of comfort indexes for open spaces (Monteiro, et al, 2011).

Studies in the area of environmental comfort and climate in open spaces presuppose the acquisition of data pertaining to environmental conditions, physical characterization of spaces and users' opinions (subjective answers). Knowledge of environmental and physical conditions, as well as users' perceptions becomes paramount for an analysis and / or evaluation of our cities / open spaces. It was observed, in the last years, that – despite the technology employed in field researches – part of the information could be obtained in a more dynamic fashion.

Thus, the development of a mobile application (OPINE) aims at speeding up and automating the acquisition, treatment and availability of collected data; as well as verifying the viability of the adequation of this methodology to the day-to-day routine of acquisition of primary data in researches which in loco measurements of environmental variables and user's perceptions.

### **Methodology and procedures**

The participative model – mobile application – aims at investigating the user's perception of environmental conditions (thermal, acoustic, daylight and ergonomic) and physical characterization of environments, with subjective answers acquired remotely.

The need for instruments applied to the more agile process of data acquisition for urban microclimatic variables (temperature, humidity, air velocity and thermal radiation) and subjective variables (perception of thermal sensation and comfort) is fundamental to the optimization of the process and to guaranteeing reliability of the data collected automatically.

The application should receive data in real-time from weather stations, so as to establish the most comfortable area and show this to the Campus user.

We chose to develop a participative model / mobile application for a few reasons:

- For the increasing quantity of users with mobile devices – Applications are increasingly gaining space on the users' daily lives, thus it is only natural to follow this trend of process automatization, a user research – in this case;
- Eliminate the need for an interviewer – The need for volunteers, or hired labour, is common practice in many data gatherings in order to approach the largest possible number of people. Furthermore, the manner in which users are sampled requires consideration, to ensure the lowest possible bias in the answers, thus ensuring a random sampling;
- Promote a more interactive and pleasant interface for the user – The user will answer a series of questions, so the more comfortable he / she is with the tool, the more reliable will the answers be;
- Ease of data acquisition – The data can be acquired at any time, unbound by interviewers' working hours. Furthermore, this application is aimed at outdoor environments, so people can answer during their displacements on foot or bicycle with no need to interrupt their activities, thus optimizing their time;
- Accuracy of the time of information acquisition – One of the great difficulties is to know if the survey was taken in the morning, afternoon or evening. With mobile acquisition, the time-stamp from the data transmission from the users' devices will enable a precise analysis of the influence of the time of day on the comfort perceptions.

### **Study area**

The OPINE app was developed to be used, in principle, in the *Campus Cidade Universitária Armando Salles Oliveira* (CUASO), São Paulo University (USP), Brazil.

According to the *Anuário Estatístico USP* (2015), on the people who are linked to USP, the majority of its population is comprised of undergraduate and graduate students (70% of the Campus occupants).

Figure 1 shows some examples of the different special conformations (streets + medians + sidewalks + green areas + buildings) which interfere on the space's surface temperature conditions faced by the users as they circulate around the Campus.

This variation occurs due to the areas being exposed to the sun or shaded. The detection of paths – or routes – more commonly taken by the users will enable verification of the spaces chosen by the users as more comfortable.

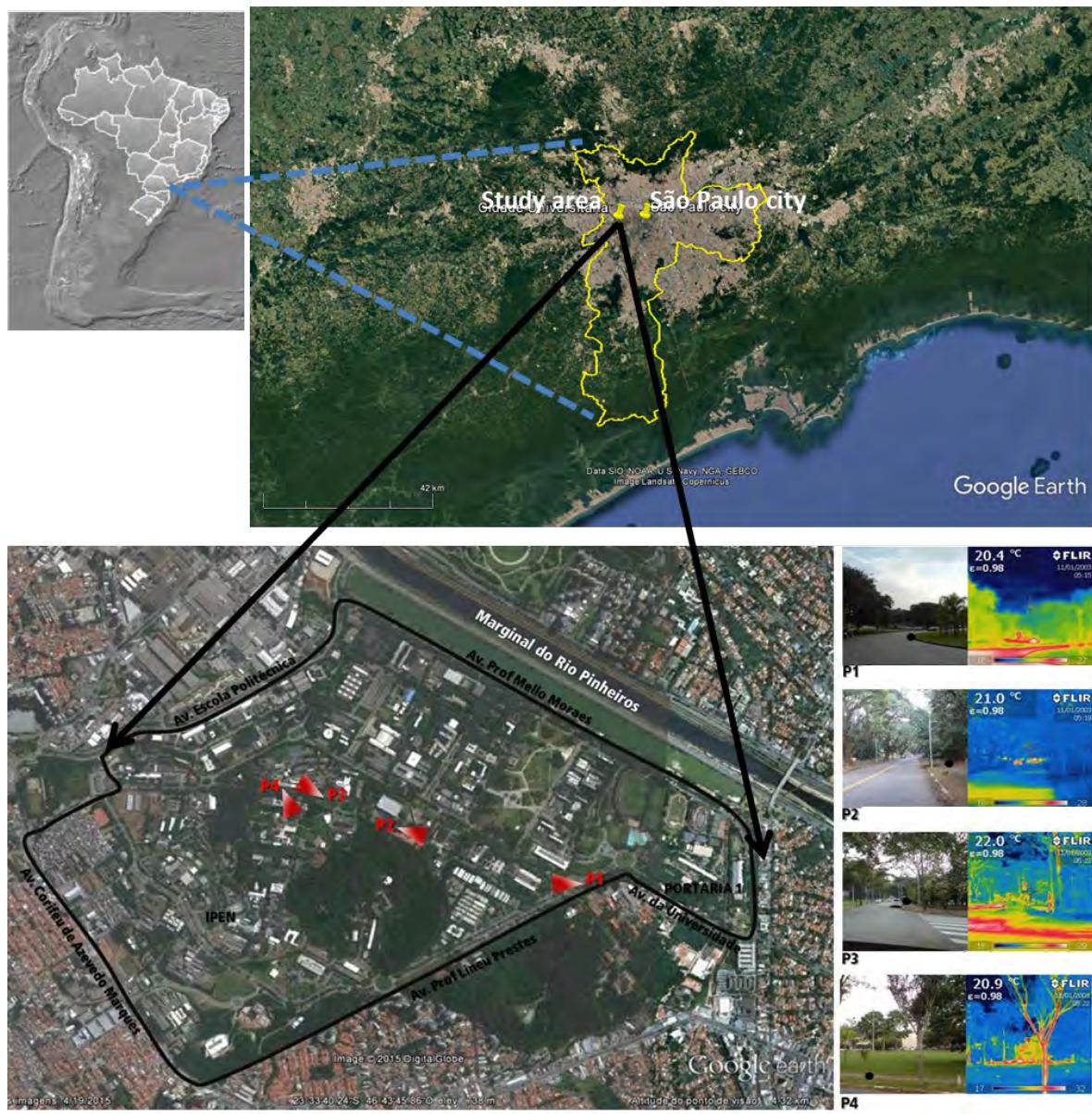


Figure 1. Map of CUASO with some thermal images taken on open spaces of the Campus.

### ***Opine – development***

The OPINE app was developed in Java programming language (Deitek, et al. 2005) and Android (Lecheta, 2015). The platform chosen for the app was the Android system, for its larger audience reach when compared to IOS – an operational system developed by Apple. Android is currently the undisputed leader in Brazil, with a 89.5% share of mobile devices. Windows Phone is second with 5.9% share and Apple is third, with 3.5% share. (Tudo Celular, 2016).

The system, as a whole, is comprised of a mobile device and two weather stations (currently under implementation), which feed a data bank with users' subjective answers and climate conditions, respectively, connected through a server.

With each answer from the users, the data is directed to the system's data bank. Figure 2 presents the process of routine development and the acquisition system. The participative model can already be used for subjective data (users' answers) acquisition.

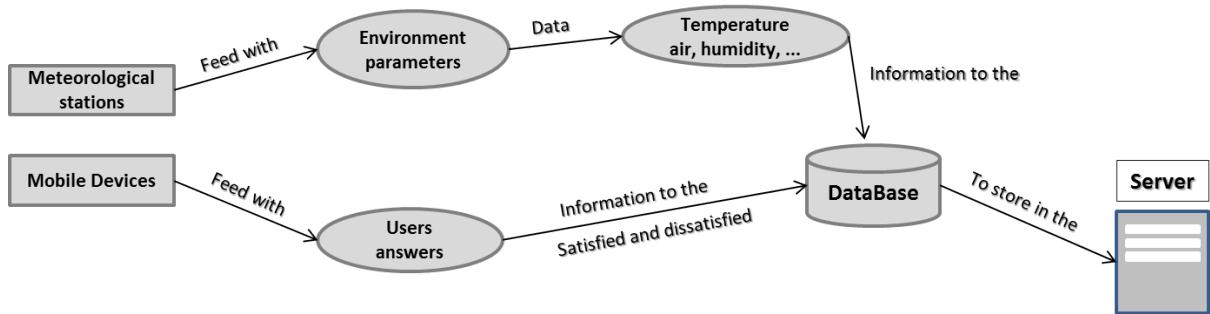


Figure 2. Development system diagram – participative model.

### ***Opine – variables for collection***

Some pre-requisites were settled upon for the development of the app: 1. Contain a clear survey; 2. Easy and quick to answer; 3. Questions and its possible answers must be easy to understand; 4. Lead users to answering all mandatory questions; 5. Use of a visual language which appeals to the target audience (students); 6. Compel the user to answer it; 7. Generate feedback which can be used in comfort indexes; 8. Ergonomic should be designed for ease of navigation; and 9. Be made so as to reach a large audience.

The user's contribution, on opening the app, is to answer questions pertaining to his / her perception of the Campus' open spaces, in regards to thermal environmental conditions, acoustics, illumination and ergonomics.

The user accesses the app through the phone's menu, by clicking the OPINE logo. The splash screen shows the slogan “Are you comfortable?” (“Você está confortável?”). Subsequently, on the MENU option, a text is shown explaining what the app is about, also making an alert on the use of the device's battery and the non-use of the information in case the user so chooses (Figure 3):

“Welcome!

This app is intended as means to obtaining, in a practical and dynamic manner, informations on users' perceptions of environmental conditions in outer open spaces of the Campus.

Your answers are very important to a critical analysis of the procedure developed for the remote acquisition of data, for evaluation of the comfort conditions of urban open spaces.

Thank you!”

After accessing the app, the user inputs some data – essential to understanding his / her positioning in the built environment, as well as information pertaining to: age, sex, height, attire, physical activity (still, walking, running...) as well as his / her mood at that specific point.

Figure 4 shows some examples of the screens for input of users' initial information.

The input of initial information is followed by nine screens which try to obtain from the user information as to his / her satisfaction as to environmental and spatial parameters of his / her current location. For these informations the user uses slide-bars going from 0% to 100% satisfaction. Figure 5 shows some of these nine screens.

Information requested are: 1. How do you feel about this place?: 2. How do you feel about air quality at this time?; 3. How do you feel about ambient noise at this time?; 4. How do you feel about light reflected from buildings, passing cars and ground at this time?; 5.

How do you feel about temperature at this time?; 6. How do you feel about the sun at this time?; 7. How do you feel about the wind at this time?; 8. How do you feel about the quantity of vegetation?; 9. How do you feel about the sidewalk?

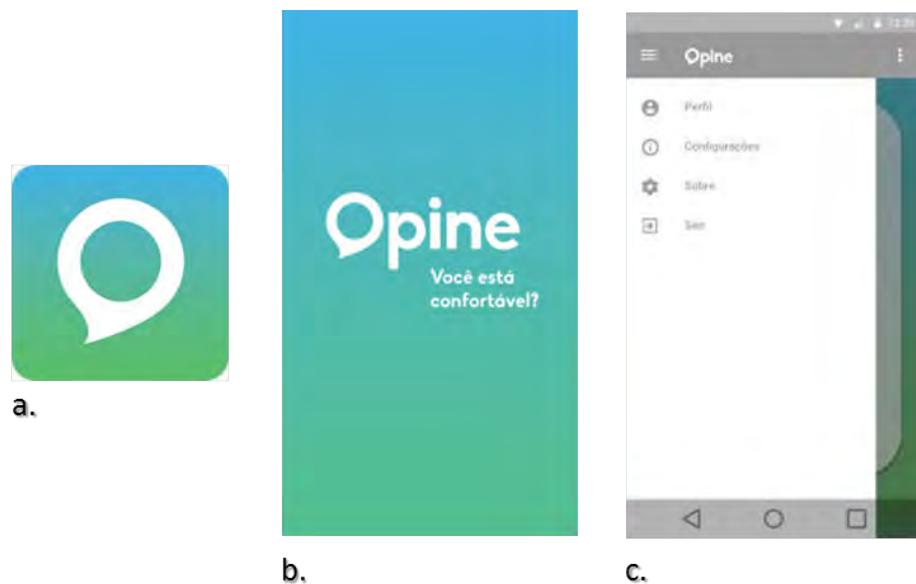


Figure 3. a. App icon / logo which will be shown on the device's menu; b. Splash screen; and; c. Initial screen - information.

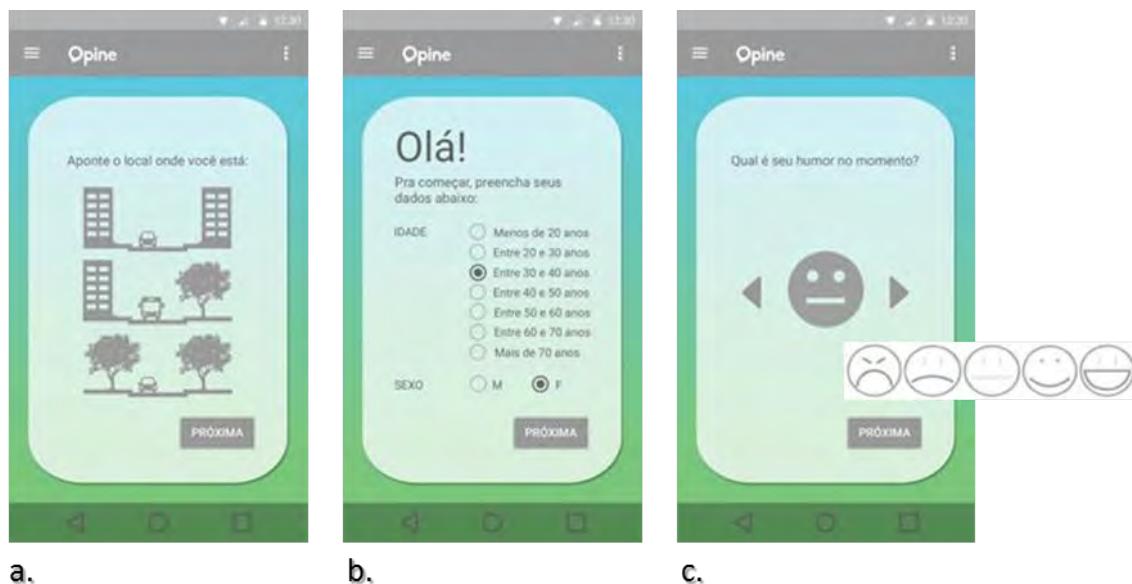


Figure 4. App screens: a. Question about user's location – and if there are more trees or buildings; b. User information (age and gender); and c. Current mood.

Three additional questions comprise the App and have more of an informative character: a. Predominance of the vegetation in the area; b. Do you consider the sidewalk width (from too narrow to too wide); and c. Please check any items (urban furniture) you miss: benches / trash bins / bicycle rack (Figure 6).

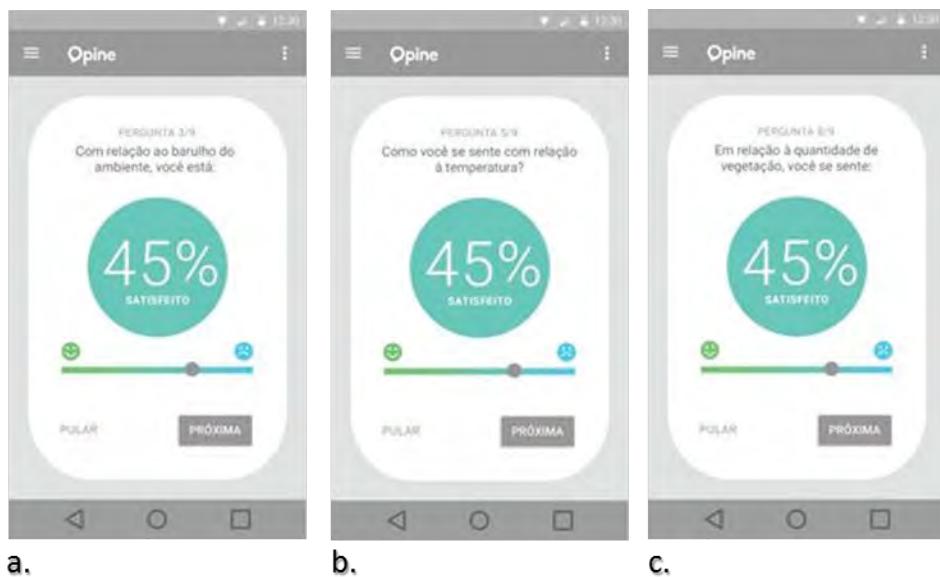


Figure 5. App screens -- user's opinion.

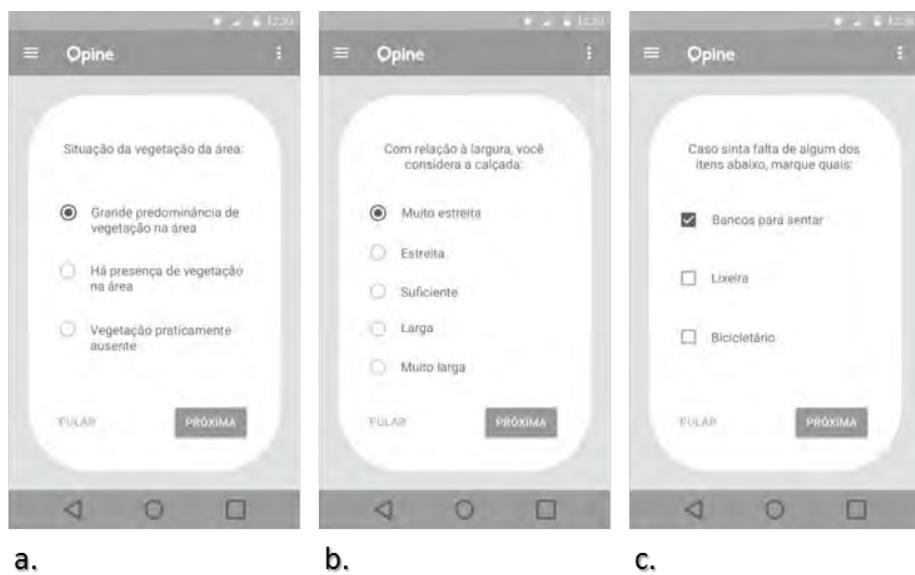


Figure 6. App screens / additional information – user's opinion

An important point to mention is that, during the development of the app, some data were fundamental to the final formatting / design. Information for the creation of screens, such as distances, widths, heights, fonts, colors, etc., are part of the “designer / programmer” domain, must be addressed in synchrony and are multi-disciplinary. Based on these informations, the programmer can reproduce the desired design in the actual app and insert images and icons created by the designer. Figure 7 presents an example of the development of the screens.

## Conclusion

We present, here, the development of a mobile application for the acquisition of data from the user. It has several desired qualities: easy understanding, clarity, organization, readability, images to make it more intuitive, does not stray from the Android model and its visual identity is related to the theme.

The app was developed in Portuguese and can, in the future, be translated to English. Its use in other cities / spaces can aid in several environmental comfort researches. Instead of the researcher going out and handing out forms, an app will aid in this task.

The greatest challenges are motivating the user to answer – recurrently – the app survey in different days, times and seasons; obtaining / creating / producing a data bank capable of subsidising the changes and / or creation of a comfort index for outdoor environments (physical and environmental characteristics), based on this user profile.

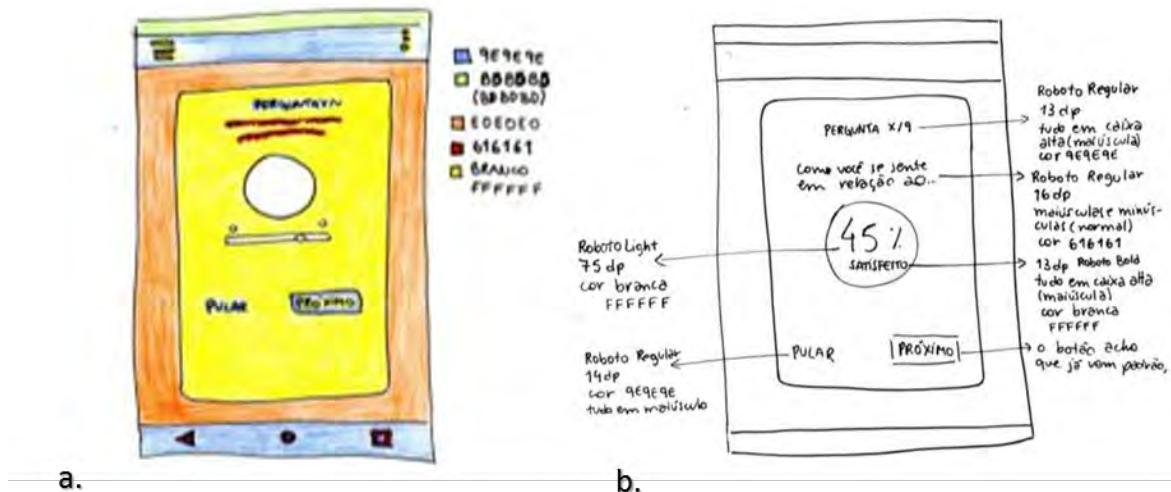


Figure 7. Creation of app screens – development.

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## References

- DEITEL, H. M. and DEITEL, P. J. Java: Como programar, 6a. Edição, 2005.
- LECHETA, R. R. Google Android 4a edição. Novatec Editora, 2015.
- MILLS, G. (2006). Progress toward sustainable settlements: a role for urban climatology. *Theoretical and Applied Climatology*, volume. 84.
- MONTEIRO, L. M.; ALUCCI, M. P. (2011) Proposal of an outdoor thermal comfort index: empirical verification in the subtropical climate. *Architecture & Sustainable Development*. Louvain-la-Veruve. Press Universitaires de Louvain, pp. 433-438.
- Oke, T.R. (1987). Boundary layer climates. 2nd ed.
- PBMC (2014). Mitigação das mudanças climáticas. Contribuição do Grupo de Trabalho 3 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas [Bustamante, M. M. C., Rovere E.L.L, (eds.)]. COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil, 463 pp.
- Tudo celular (2016). Disponível em: <http://www.tudocelular.com/windows/noticias/n60530/windows-phone-crescimento-brasil.html>. Acesso em 27 de janeiro de 2016.
- Universidade de São Paulo. Anuário Estatístico (2015). Disponível em <https://uspdigital.usp.br/anuario/AnuarioControle>. Acesso em 25 de dezembro 2015.



# PLEA 2017 EDINBURGH

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## **Comfort as a strategic design ingredient to support pro-environmental behaviour in sustainable student accommodations**

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**Abstract:** One of the avenues design can alleviate the environmental impact of sustainable residential buildings is by promoting pro-environmental behaviours. However, many environmentally relevant household behaviours are habitual, and may be difficult to change once they have sunk into routines. Research suggests that habits are established in young adulthood, and that well-designed environments may help the uptake of pro-environmental behaviours. Therefore, students moving into accommodations designed with a sustainability driven ethos may provide a unique opportunity to establish sustainable habits. The study investigates how sustainable student accommodations shape environmental behaviours and practices, with the aim of informing future design decisions of sustainable student accommodations. Twenty (n=20) interviews were conducted with students living in British sustainable student accommodations and analysed using Grounded Theory. The results show that perceived comfort is a core influencing factor in how students interact with their accommodations. In cases where the design features did not support the comfortable enactment of mundane activities, students found ways to circumvent or adjust features, resulting in less environmentally friendly outcomes. Conversely, where features were comfort-considerate, usage was as intended, ensuring sustainability goals. Finally, the analysis crystallises a map of key design elements, their relation to comfort and the final behavioural outcomes.

**Keywords:** student accommodations, BREEAM, design features, comfort, pro-environmental behaviour

### **Introduction**

Residential buildings are responsible for nearly a third of UK's greenhouse gas emissions (DBEIS, 2017). Emission reduction of buildings can be achieved by various ways, such as changing the energy provision of the supply chain, improved building design, and through energy efficiency and curtailment behaviours (Gardner and Stern, 2008). The design of sustainable residential buildings might have the potential to moderate the environmental strain and reduce the energy and resource appetite of buildings by applying contemporary 'green' building practices, such as the use of efficient materials or sustainable features to name but a few (Friedman and Wybor, 2016). However, residents often use sustainable buildings and its appliances in unsustainable ways, offsetting the expected gains (Asmar and Tilton, 2015). Understanding the complex tangle of residents' everyday environment related behaviours and practices performed in sustainable buildings might inform the design of sustainable residences, enabling it to create physical surroundings with higher level of behavioural resilience.

Architectural design has the potential to support learning, to unleash creativity, to boost work performance, to promote social connectedness, or even to facilitate faster

healing (Augustin et al., 2009). Behaviour intervention strategies integrated into architecture have been used in certain areas, such as health, education, crime prevention or social behaviour promotion in traffic (Crowe, 2000; Kopec, 2012). Nevertheless, how and to what extent architectural design of sustainable buildings may influence environmentally relevant behaviour is not clear (Clarke, 2013; Wever, 2012).

The investigation of sustainable student accommodations could identify good opportunities to promote pro-environmental behaviour by design. Students, as young adults, generally have high environmental awareness, tend to be more flexible and open to change, and may also be more receptive to adopt pro-environmental behaviours than other age groups (Arnett, 2015; Friedman and Wybor, 2016; Garabuau-Moussaoui, 2011). Furthermore, the transitional stage of young adulthood is characterized by contextual changes, such as moving into student accommodations, which could act as a window of opportunity to engage in new pro-environmental behaviours and habits (Verplanken et al., 2008). Here it is significant that a number of sustainable buildings have been found to support certain pro-environmental behaviours (Khashe et al., 2015; Wu et al., 2013). It is therefore possible that well-designed student accommodations could help to promote and support environmentally friendly behaviour.

Although the time spent in student residences is generally short, the environmentally significant behaviours and habits formed in this period may become part of students' identity and therefore continued to be performed in their adult life (Crompton and Kasser, 2009; Garabuau-Moussaoui, 2011). In other words, the contribution of sustainable student accommodations may continue beyond the period students reside in the building itself.

The present study aims to develop understanding on the many facets of environmentally significant domestic behaviours performed in sustainable student accommodations and focuses on how the sustainable built environment shapes the environmentally relevant behaviour of residents.

## **Method**

Given the unexplored nature of the investigated area, the study uses Grounded Theory (Charmaz, 2014) as research methodology. The interviews conducted were used to develop a theoretical understanding of how sustainable student accommodations shape environmentally relevant behaviours and practices.

## **Participants**

Twenty ( $n=20$ ) participants were sampled from four sustainable student accommodations across the UK. All accommodations were BREEAM (Building Research Establishment Environmental Assessment Method) Excellent certified. BREEAM is an established method of assessing, rating and certifying buildings with high environmental commitment (BRE, 2017). All participants had already spent more than two months in the studied accommodations, meaning that they probably all were familiar with their new environment and able to have an in-depth conversation about their experiences with the accommodations. Further site and participant characteristics are presented in Table 1.

Table 1. Characteristics of the sites and participants

Site no	Location	Site size	Room type	Number of participants	Gender	Nationality
1	South Wales	5 buildings 476 beds	Single, En-suite	5	2 females 3 males	2 British 3 Overseas
2	London	3 buildings 355 beds	Single, En-suite	3	3 males	3 British
3	Manchester	8 buildings 1367 beds	Single, En-suite	7	3 females 4 males	5 British 2 Overseas
4	Norwich	1 building 231 beds	Single, En-suite	5	2 females 3 males	5 Overseas
Total				20	7 females 13 males	10 British 10 Overseas

### ***Data collection***

The primary data was collected through face-to-face, in-depth, semi-structured interviews. Participants were invited to join the study via emails delivered by their accommodation providers. All interviews took place in a quiet and comfortable venue, close to the studied environments, usually in a communal but tranquil location on campus. Each interview lasted for approximately one hour. The interviews were conducted in February, March, April and end of November 2016. The anonymity of participants was ensured by assigning pseudonyms that are used in all subsequent reports.

The interviews explored the following topics: the experience of moving into sustainable accommodations; the experience of living in sustainable accommodations; the environmentally relevant practices performed in sustainable accommodations; the perceived influence of the physical environment on environmentally significant behaviours and the perceived influence of the social environment on environmentally significant behaviours. The interviews started with a less structured shape and evolved towards a more structured form as the research progressed, in line with Grounded Theory. The interview schedule consisted of open-ended questions allowing participants to freely reveal their thoughts, feelings and experiences.

The interview data was complemented by diaries and photos participants took for a week prior to the interviews. Participants were asked to describe in 100 words a day, their environment affecting actions performed in the student accommodations, and to take photos on the same subject. The diaries helped participants focus their attention on the topic, making the interviews more fluent. The diary entries, were sent to the researcher the day before the interview, and were used to develop specific questions for each participant. Finally, data was complemented by a demographic questionnaire composed of ten questions prompting for general information, such as age, gender, length of stay in the sustainable accommodation, type of residence and student awareness on the sustainability rating of their accommodations.

### ***Analytic Approach: Grounded Theory***

The research used as overarching methodology Grounded Theory (Charmaz, 2014) and consisted of iterative cycles of closely coupled data gathering and data analysis. Each cycle of data gathering and analysis involved collecting all data from one single site and performing a preliminary analysis on it. This approach allowed to develop an early

understanding on how environments were being used by students. Subsequently, it contributed to refining the interview schedule as the study progressed, leading to more specific questions around the use of design features integrated in the accommodations. Finally, the pre-analysed data from all four sites was merged and analysed together.

The analysis of the interviews identified stories of key actions that might have had an environmental impact, such as using natural and artificial lights or heating practices. These environmentally affecting ways of doing involved the use certain design features of the accommodations, such as windows and blinds, light controls or radiator controls. The comparison of the actions, however, revealed that the use of a given feature was sometimes environment friendly while other times it was less so. For instance, certain students got through the day without using the artificial lights in their rooms, while others relied heavily on artificial lights during the day. Going forward, the analysis focused on understanding why the uses differed. By comparing the contrasting cases usage patterns emerged, where the way of using each design feature seemed to be associated with a set of 'needs' students were trying to satisfy.

## Results

The study surfaced a set of needs that students were aiming to fulfil while using the design features of the accommodations. The identified needs are comfort, control, privacy, ease of use and hygiene. Moreover, the direction of environmentally affecting behaviours seems to be swayed by how far the sustainable design features consider and satisfy students' needs. In cases where design features do not support the identified needs, students find ways to circumvent or adjust features, resulting in less environmentally desirable outcomes. Conversely, where features are sensitive to the needs that emerged from the analysis, use is as intended, ensuring positive environment related behavioural negotiations. Figure 1 presents the map of design features surfaced from participants' recounts, the relation of design features with student needs, and the final behavioural outcomes. The continuous lines highlight the scenarios where the needs were satisfied and use was environmentally supportive, while the dashed lines show the cases that led to less environmentally friendly behaviours since needs were not supported by the design features.

Privacy, in the sense of visual privacy (Altman, 1975), in student rooms prevailed as a very pertinent need, even more that the rooms were the only private space students had in the studied accommodations. Student narratives linked privacy to the large, double glazed windows meant to capture daylight and to reduce artificial light use in sustainable buildings. However, the interviews revealed that windows might sometime cause privacy issues that had the opposite behavioural and environmental effect than the one originally intended. It was quite common that students, especially the ones living on the ground floor, said that they felt uneasy because people could see into their rooms so they closed the blinds and used artificial lights.

*"Everyone can see from the outside as I like my privacy I always down the curtain and I use my lamp. "(Felix, Site 1)*

In contrast, when design resulted in a bright space with no privacy issues, the behavioural and environmental outcome was as expected and served sustainability goals.

*"I never have the blinds down really because I think it's just so nice to get the sunlight in and just work with that. "(Jack, Site 2)*

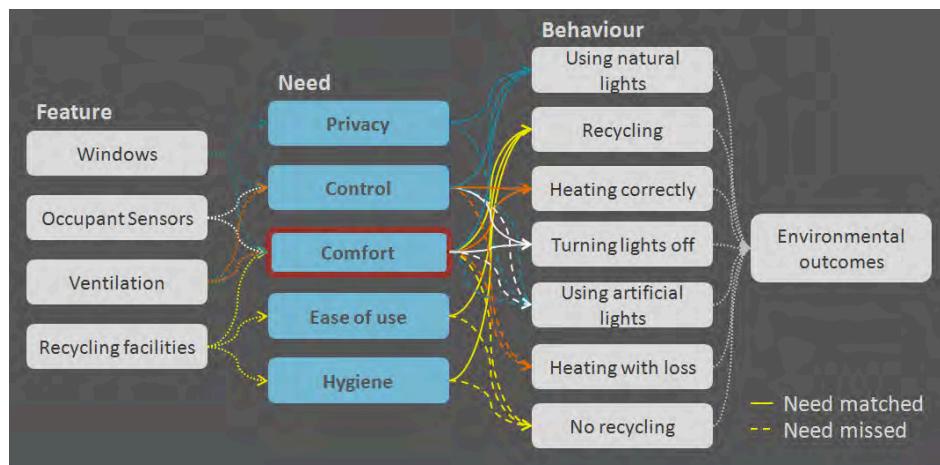


Figure 1. Map of features, needs and behavioural outcomes

Privacy is recognized in student residence focused studies as major factor in shaping residents' satisfaction (Amole, 2005) . The present finding enhances the knowledge base by linking visual privacy and sustainability through identified behaviour patterns that pursue the restoration of privacy while resulting in higher energy use.

Stories of actions involving several design features, identified a strong need for control, in line with earlier findings showing that having control over the indoor environment improves the comfort and satisfaction of building users (Frontczak and Wargocki, 2011). Beyond the comfort and satisfaction implications, in the present study the availability of control over the design features mentioned by respondents, was connected to how sustainably the features were used. For instance, occupancy sensor controlled lights in the kitchen and living area of student flats, were meant to reduce electricity waste by eliminating the unwanted effect of leaving the lights on. Nevertheless, where occupant expectations for lighting levels and available control strategies did not match, waste inevitably happened:

*"Let's say you are going in, in the evening to get some water or even during the day, even during the day there is a lot of light coming in and then when you are going into the kitchen or to bring some water all the four lights turn on,... automatic sensor is even during the day, they turn on even if there is plenty of light... and it makes no sense and it is really annoying." (Harry, Site 2)*

On the other hand, where sensors were complemented with manual control, students used the lights in more environmentally friendly ways:

*"if I'm making my breakfast at seven then I'll turn it off" (Marion, Site 4)*

*"I always switch off the light in the kitchen even if it turns off by itself" (Zia, Site 4)*

Residents also reported appreciation of the dual control system:

*"I like it, I think it's useful, it doesn't do it (manage lights) intrusively," (Wayne, Site 3)*

Comparison of light control systems in office environments (Aghemo et al., 2014) showed personnel preference for manual control in addition to automatic light control system, which is in line with the present findings. Moreover, the current study highlights the behavioural responses of residents in the scenarios with and without manual control, and suggests that the environmentally friendly behaviour of using the lights only when needed might be more frequent when dual control is provided.

Ease of use and hygiene were two needs that appeared to connect recycling related devices and student practices. Where signs from waste receptacles were clearly suggestive of intended use, students reported recycling actions:

*"So you know, recycling, there is a big sign on our bins saying it's a recycle bin and we've got compost bins... I think it's convenient for everyone so a lot of people are choosing to do that way." (Jaden, Site 2)*

In contrast, where the signage on outside containers was uniform and did not help properly identify the type of waste the containers should hold, students reported confusion and lack of recycling:

*"I don't know, because they are all just the same bins that have the exact same label, they don't stand out for me." (Harry, Site 2)*

The recounts suggest that students need to instantly recognize how to sustainably use the elements of their physical surroundings in order to be able to act in an environmentally considerate manner. The need for ease of use may be fulfilled by the clear signals incorporated in the design, for how to use waste management facilities. This idea is well-transmitted by the concept of perceived affordance (Norman, 2013). Furthermore, the findings resonate with earlier empirical studies that underline the importance of clear cues for action in recycling activities (Duffy and Verges, 2009).

The perceived hygiene or cleanliness during the manipulation of the waste bins, surfaced as a theme relevant enough to shatter strong recycling intentions:

*"From the start we moved in, people just became put off putting things in that bin very quickly... because it got dirty, it was very-very small, very filthy to install a bin lining to it... I cleaned this entire thing in my shower-cubicle a few times which is utterly disgusting trying to remove things... so at that point we just didn't bother any more..." (Harry, Site 2)*

The influence of perceived hygiene on waste management behaviour has been confirmed by empirical findings in relation to using the food waste caddies for food waste disposal (Metcalfe et al., 2012). Perceived hygiene or cleanliness of the caddy was, just as in the present case, a deterrent to pro-environmental actions despite existing pro-environmental intentions and attitudes.

Although, several types of needs emerged from student recounts, comfort was the most prevalent, and was linked with the use of all sustainable design features students mentioned. Furthermore, interviews suggest different aspects of comfort, such as thermal comfort, good perceived air quality, and visual comfort, which fits literature investigating comfort and indoor environmental qualities (Frontczak and Wargocki, 2011; Al horr et al., 2016).

Thermal comfort and perceived air quality emerged to be closely interlinked in the way users experienced and used the indoor environment. This is in line with earlier empirical findings suggesting that thermal comfort is correlated with perceived air quality (Zhang et al., 2011). When the perceived air quality was reported to be good - which was attributed to the trickle vents on the window - students only reported to open the windows when they felt it was too hot in their rooms.

*"The air quality is really good because it's coming straight through under the window and it's right where you sleep as well... if I'm hot I turn the radiator off and then I open the window." (Jack, Site 2)*

In contrast, in environments where windows were conveyed to be the only available ventilation devices in student rooms, residents perceived the air as 'suffocating' as some phrased it, and subsequently kept the windows open while using the radiators:

*"I want to have fresh air coming in so let my window a little bit open just for the ventilation and then turn the radiator on." (John, Site 1)*

The above way of airing a room wastes energy and counters the thermal performance of even the most energy efficient building. The results support earlier reports which mentioned use of radiators with open windows in order to regulate the temperature in student accommodations (Clear et al., 2015). The present study puts forward an explanation for the phenomena, suggesting that residents' attempts to ensuring good air quality may be one of the reasons for opening the window while the radiator is on.

The importance of visual comfort was confirmed by residents through their narratives of actions involving natural and artificial light use. In certain cases, where residents reported reliance on artificial lights during the day, their action was reasoned with the experience of glare caused by direct sunlight coming through the window.

*"My lights are often turned on ... window shade is kept down as when it is up it is too bright and I can't see the computer screen."* (Sione, Site 1)

Conversely, when the occurrence of glare was not reported, students used natural light for work.

*"I don't turn on the light in daytime"* (Zia, Site 4)

*"I never have the blinds down really because I think it's just so nice to get the sunlight in and just work with that"* (Jack, Site 2)

Visual comfort, including glare is a widely researched topic with implications on human performance in offices and educational spaces (Osterhaus, 2005). The present paper acknowledges the importance of visual comfort based on student recounts and further documents environment affecting behaviour patterns that occur in order to re-establish comfort.

In summary, the analysis suggests that environmentally relevant behaviour in sustainable residences might be guided by the need considerate quality of sustainable features. The need considerate quality is defined as compliance with students' needs for comfort, control, privacy, ease of use and hygiene. Finally, comfort with its various facets was identified as the most ubiquitous need and was associated with all mentioned sustainable features and all environment affecting behaviours.

## Conclusion

The paper argues that comfort is a decisive need that has to be considered while designing sustainable student accommodations that promote sustainable behaviour. The sustainable features considered during the design ought to address sustainability on a technical level but also have to be mindful of residents' needs in general and comfort in particular. Understanding comfort with the various nuances it holds for each design feature integrated in sustainable student accommodations, may be key to ensuring sustainable use by design. Although contemporary sustainable student residences do integrate technically sustainable features on one hand, and do aim to design comfortable student environments on the other (Friedman and Wybor, 2016), the sustainable use of the integrated sustainable features needs to be further considered from a comfort perspective in order to support proper use.

## References

- Aghemo, C., Blaso, L., Pellegrino, A. (2014). Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices. *Automation in Construction*, 43, pp. 10–22
- Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5, pp. 1–11

- Altman, I. (1975). *The environment and social behavior: Privacy, personal space, territory and crowding*. Monterey, California: Brooks/Cole
- Amole, D. (2005). Coping Strategies for Living in Student Residential Facilities in Nigeria. *Environment and Behavior*, 37(2), pp. 201–219
- Arnett, J. J. (2015). *Emerging Adulthood*. Second edition. New York: Oxford University Press
- Asmar, M. E., Tilton, C. (2015). Student Housing Energy Consumption: A Comparison of Chilled Water, Heating, and Electricity Use. *Procedia Engineering*, 118, pp. 1038–1043
- Augustin, S., Frankel, N., Coleman, C. (2009). *Place Advantage: Applied Psychology for Interior Architecture*. Hoboken, New Jersey: John Wiley & Sons
- BRE. (2017). Building Research Establishment Environmental Assessment Method (BREEAM). Available from: <http://www.breeam.org/>
- Charmaz, K. (2014). *Constructing Grounded Theory*. 2nd Edition. London: SAGE Publications
- Clarke, J. L. (2013). *Sustainable buildings: Sustainable behaviour? To what extent do sustainable buildings encourage sustainable behaviour through their design, construction, operation and use?*. PhD. Kingston University
- Clear, A. K., O'Neill, K., Friday, A. (2015). Designing for transitions to sustainable lifestyles. *interactions*, 22, pp. 56–58
- Crompton, T., Kasser, T. (2009). *Meeting environmental challenges: the role of human identity*. Surrey: WWF-UK
- Crowe, T. D. (2000). *Crime Prevention through Environmental Design: Applications of Architectural Design and Space Management Concepts*. Woburn, MA: Butterworth-Heinemann
- DBEIS. (2017). Department for Business, Energy and Industrial Strategy: 2016 UK Greenhouse Gas Emissions, Provisional Figures - Statistical Release. National Statistics, Retrieved from <https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2016>
- Duffy, S., Verges, M. (2009). It Matters a Hole Lot: Perceptual Affordances of Waste Containers Influence Recycling Compliance. *Environment and Behavior*, 41, pp. 741–749
- Friedman, A., Wybor, J. (2016). *Innovative student residences: new directions in sustainable design*. Mulgrave, Australia: The Images Publishing Group Pty Ltd
- Frontczak, M., Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment*, 46, pp. 922–937
- Garabuau-Moussaoui, I. (2011). Energy-related logics of action throughout the ages in France: historical milestones, stages of life and intergenerational transmissions. *Energy Efficiency*, 4, pp. 493–509
- Gardner, G. T., Stern, P. C. (2008). The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change. *Environment: Science and Policy for Sustainable Development*, 50(5), pp. 12–25
- Khashe, S., Heydarian, A., Gerber, D., Becerik-Gerber, B., Hayes, T., Wood, W. (2015). Influence of LEED branding on building occupants' pro-environmental behavior. *Building and Environment*, 94, pp. 477–488
- Kopec, D. (2012). *Environmental Psychology for Design*. 2nd Edition. New York: Fairchild Books
- Metcalfe, A., Riley, M., Barr, S., Tudor, T., Robinson, G., Guilbert, S. (2012). Food Waste Bins: Bridging Infrastructures and Practices. *The Sociological Review*, 60(2), pp. 135–155
- Norman, D. A. (2013). *The design of everyday things*. Revised and expanded edition. New York: Basic books.
- Osterhaus, W. K. E. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy*, 79(2), pp. 140–158
- Zhang, H., Arens, E., Pasut, W. (2011). Air temperature thresholds for indoor comfort and perceived air quality. *Building Research & Information*, 39(2), pp. 134–144
- Verplanken, B., Walker, I., Davis, A., Jurasek, M. (2008). Context change and travel mode choice: Combining the habit discontinuity and self-activation hypotheses. *Journal of Environmental Psychology*, 28, pp. 121–127
- Wever, R. (2012). Editorial: Design research for sustainable behaviour. *Journal of Design Research*, 10 (1-2), post-print version
- Wu, D. W. L., DiGiacomo, A., Kingstone, A. (2013). A Sustainable Building Promotes Pro-Environmental Behavior: An Observational Study on Food Disposal. *PloS one*, 8(1), e53856



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Circadian House as a vision for healthy and human-centric building design

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**Abstract:** Much attention on sustainable buildings has been put on energy aspects. However, health is the most precious resource we have, and energy is only one aspect of sustainability. A primary goal for sustainability should be to sustain good human health and provide healthy living environments. This was the starting point for a series of workshops with international experts. The result is a vision to realize healthy homes that support the different biological needs of their occupants with a focus on the entrainment of circadian rhythms, sleep-wake cycles, light exposure, thermal comfort, air quality, and contact to outdoor environments. Three key principles were identified: *Live in balance with nature, Adaptability and Sensibility*. Furthermore, those principles are supported by ten key factors including: *Variation, Stimulation/absence of stimulation, Outdoor/indoor relation, Light/darkness, Electrical lighting, Cool/warm, Silence/sounds, Rest/activity, Control and Flexibility related to seasons*. The principles and guidelines presented here can be used to guide and improve the design of residential buildings of all types, including apartment buildings, and are applicable to both new and existing dwellings.

**Keywords:** Residential buildings, health, indoor climate, circadian rhythm, daylight, thermal comfort

### Introduction

Much attention on sustainable buildings has been put on energy aspects. However, health is the most precious resource we have, and energy is only one aspect of sustainability. A primary goal for sustainability should be to sustain good human health and provide healthy living environments. This was the starting point for a series of workshops with international experts initiated by the VELUX Group, based on a wish to start a discussion on how to create healthier residential buildings.

Three key principles were identified: Live in balance with nature, Adaptability and Sensibility. Furthermore, those principles are supported by ten key factors including: Variation, Stimulation/absence of stimulation, Outdoor/indoor relation, Light/darkness, Electrical lighting, Cool/warm, Silence/sounds, Rest/activity, Control and Flexibility related to seasons.

The principles and guidelines presented here can be used to guide and improve the design of residential buildings of all types, including apartment buildings, and are applicable to both new and existing dwellings (Circadian House, 2013).

### Methods

In the context of this paper, a Circadian House is understood as a dwelling that promotes health by entraining and synchronising the circadian rhythms of its occupants to the 24h day-night cycle and the seasonal changes of day length.

This paper is based on discussions and findings of 5 workshops; "Light and circadian rhythms", "Indoor climate", "The historical perspective", "What to monitor and how" and "Condensation of the specifications" (WS 5). The workshops were carried out by scientists and consultants specialized in healthy buildings, indoor environment, architecture and planning from November 2012 to August 2013. See the Acknowledgements section.

## **Results**

It is not possible to include all results in this short paper. In the following we will highlight selected key results organised around a selection among the ten key factors.

### ***Contact to nature***

Dwellings should have at least one outdoor or semi-outdoor space (e.g. a garden, terrace or balcony) that provides direct contact to nature. Research studies show that improved mood and reduced stress are consistent benefits of living in close contact with nature (Veitch & Galasiu, 2012).

Outdoor spaces must be treated as an extension of the house and designed to inspire the occupants to spend as much time as possible outside, offering a close contact to nature in all seasons of the year. Outdoor spaces should be designed for a variety of activities such as dining, playing, working, relaxing etc. People affected by the seasonal changes in day length will benefit from extra exposure to high levels of daylight in outdoor and semi-outdoor spaces. Also, exposure to daylight and sunlight outside allows our body to produce vitamin D, which people in modern societies often lack due to the large amount of time spent indoors. Balconies and terraces should be shielded from wind and have good connections to relevant rooms of the house in order to maximise their use.

### ***View to outside***

Views to the outdoor surroundings are crucial in order to maintain contact with nature and satisfy our needs for orientation in time and place while indoors. There is clear evidence of the benefits of window views, particularly views offering contact to life and nature. A good view can have restorative benefits (leading to e.g. stress relief) and sometimes even result in quicker recovery time after illness and less post-surgery pain medication.

It is important to analyse view content on-site and make sure that all main living and activity rooms in the house have generous views to the sky and ground, and to natural and/or urban landscapes around the house. Shading systems should be designed so that adequate views to the outside can be maintained in the rooms even at moments when it is necessary to block direct sun penetration. To this effect, it is important to consider proper control of sunlight in summer (Kaplan, 2001; Kellert, 2008).

### ***Healthy light***

Light is used by individuals for image forming light detection (vision) and for a variety of non-image forming light detection (non-vision) tasks including daily time cues for sleep/wake cycles and alertness levels. In addition, there is increasing evidence that human biology can be affected by changing light levels and exposure across seasons. Seasonal depression has been linked to reduced light exposure during the winter period, and attenuated levels of vitamin D can increase vulnerability to both developmental and somatic diseases in adults (Wirtz-Justice et al 1996). It should be noted that UV light also is a strong germicide that can help prevent the spread of some diseases in buildings.

Healthy lighting should consider the following factors:

- The total daily light dose;
- Healthy light is linked to healthy darkness at night;
- Light sources with a broad daylight spectrum;
- Light received at eye level;
- Levels of UV-rich light reaching the skin;
- Timing, variation and duration of light exposure over the day and across the seasons

The intensity, spectrum and timing of light exposure are critical factors in setting and maintaining our circadian rhythms, which plays a key role in the regulation of sleep/wake cycles. This is crucial as sleep disruption has been linked to poor cognitive function, stress, depression, poor social interaction, metabolic and cardiovascular disease, increased risk of infection and even cancer. Outdoor light levels allow us to regulate sleep/wake cycles, levels of alertness and the synthesis of vitamin D. The reality is, however, that we spend most of our time indoors where we are often only exposed to relatively low light levels and a limited range of the electromagnetic spectrum, and where the patterns of light and darkness occur at irregular intervals. Collectively, the consequences of poor light exposure and the subsequent impact upon health are placing a substantial burden on the individual, society and the broader economy.

Morning light is the most important signal to align our body clock, and increases alertness as well as human performance at the beginning of the day. Whereas reduced light levels in the evening promote sleep at night. For those times when seasonal daylight is not available in the morning, electric lighting can be used to support our non-visual light needs; mimicking the morning, daytime and evening periods in spectrum, intensity and dynamics. Although much is still unknown about the specifics of how light interacts with our non-visual light systems, the data we have already can be used to suggest some important approaches to the nature of daily light exposure:

- The intensity of light should provide opportunities for exposure to high daylight levels at the level of the eye, within the range of more than 1,000 lux up to around 5,000 lux, and should be designed to minimize visual discomfort (Wienold & Christoffersen, 2006).
- The light dose per day exposed to >1,000 lux should on average be more than 200 minutes with high intensity boosts, especially, in the morning (Veitch & Galasui, 2012).
- Good spatial distribution of daylight and sunlight is achieved by distributing windows in multiple external walls and the roof rather than placing them with only one orientation.
- Daylight with minimal spectral filtering should be delivered at those times of day when it is most needed for circadian regulation.
- A dwelling should follow the natural cycle of light and dark exposure - allowing high exposure to daylight in rooms used in the morning and in the main activity rooms used throughout the day, and complete darkness in the bedrooms at night.
- It is important to carefully consider exposure to darkness during the sleeping periods – as circadian and alertness regulation requires both light and dark periods over the day.

### ***Healthy Thermal Environment***

Preferably indoor temperature varies over the course of the day, in parallel with the outdoor temperature, which typically increases during the day and drops during the night. The indoor temperature should also follow the seasons (with limitations, of course), with minimum levels during the winter and maximum levels in summer (Brager & de Dear, 1998).

Solar gains through windows have a large impact on the indoor temperature and should primarily be controlled with shading. Solar gains provide spatial variation of temperature in the rooms with local warm and cool spots. During winter with little solar gains, a local 'hot spot' should be provided for in e.g. the living room, typically with a high temperature (vertical) radiant heat source. This 'hot spot' allows the occupants to seek a warm or cool position in the room that suits them and may thermally differ from the position of others in the same room. This 'hot spot' can look like a fireplace or gas stove in older houses, but then in a modern form without the air pollution side effects, e.g. hot water based local heating systems.

Architectural spaces should ideally promote people to have an active and healthy lifestyle, as opposed to being more passive. A thermally comfortable environment is not necessarily one that favours physical health. An example is a study (Lichtenbelt & Kingma, 2013), which showed that for persons exposed to an indoor temperature at the low end or even just below the comfort range, non-shivering thermogenesis is activated which leads to increased metabolism. It is thus a quality of the indoor environment if there is some temperature variation and temperatures in winter are a bit on the cold side (and in summer on the warm side).

In summer the main issue is to keep the dwelling cool and avoid too high temperatures from excess solar gains. Overheating can normally be avoided by the use of solar shading and natural ventilation through window openings. Additional summer ventilation can be achieved by cross ventilation or stack ventilation (e.g. with windows and/or skylights in adjacent walls/roofs). Bedrooms are particularly important and must be designed and located to minimise overheating, e.g. by choosing a north/east location.

## **Discussion**

During the workshops, several fundamental questions were asked about the link between housing quality, indoor environment, circadian rhythms and health. Questions like: Can a house really support circadian rhythms? Not by just providing for the adequate amount of daylight given the time of day, but also, e.g. by allowing indoor temperatures to follow (to a certain extent) the variation in outside temperatures. Can a building's design really support a healthy and active lifestyle? And how can the indoor environment in our homes promote comfort and wellbeing, rather than just maintain acceptable indoor conditions? In the 1860s, Florence Nightingale identified five essential points in securing health in dwellings: pure air; pure water; efficient drainage; cleanliness; and light, especially sunlight. "Do not build good hospitals, build good homes" is her famous quote (still very true).

## **Conclusions**

The result of the workshops is a vision to realize healthy homes that support the different biological needs of their occupants. Based on the discussions, the core elements of a Circadian House have been defined under 3 key principles and 10 key factors.

### **Key principles**

- Live in balance with nature - A house in balance with nature allows the occupants to live with and follow the daily and seasonal cycles of the outdoor environment.
- Adaptability - A house whose space and occupants can adapt to changing conditions (daily, seasonal) and needs.
- Sensibility - A house that provides protection against harmful substances, which humans cannot sense, and allows freedom to control parameters that can be sensed.

## **Key factors**

- Variation: the focus on nature's cycles implies that the indoor environment should vary in time and space rather than target uniformity or non-variability.
- Stimulation/absence of stimulation: The level of stimulation from environmental factors (light, sound, air, temperature) should be higher during day than night.
- Outdoor/indoor relation: Outdoor and semi-outdoor areas are designed to be inspiring and easily accessible; and occupants are able to follow (changes in) outdoor conditions in all main living areas of the house.
- Light/darkness: Exposure to high levels of daylight are needed in the main living areas of the house during daytime, with special attention to the rooms that are mainly used in the morning, whereas the bedrooms need to provide complete darkness at night time.
- Electrical lighting should follow, support and supplement change and variation in the light spectrum and intensity through the course of the day and distribution in space.
- Cool/warm: The house should provide temporal and spatial variation in the thermal environment that are logical (and e.g. follow – to a certain extent) outside temperature variations.
- Silence/sounds: The presence of sound and contact to sounds from outdoors are desired during daytime, whereas quiet spaces are needed at night time.
- Rest/activity: The house design should inspire the occupants to be active, but also have areas for rest and restitution.
- Flexibility related to the seasons: the use of outdoor and semi-outdoor spaces should be stimulated outside the heating season.
- The occupants should be able to control the systems that influence parameters that can be sensed, e.g. like lighting level, air quality and indoor temperature.

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## **References**

- Boyce, P. R., Hunter, C., & Howlett, O. 2003. The benefits of daylight through windows. Troy, NY: Lighting Research Center. (<http://www.lrc.rpi.edu/programs/daylightDividends/index.asp>).
- Brager GS and de Dear RJ, 1998. Thermal adaptation in the built environment: a literature review. Energy and Buildings, Volume 27, Issue 1, February 1998, Pages 83–96.
- Brainard GC and Veitch JA, 2007. Lighting and Health workshop – final report based on a workshop session at the Commission Internationale de l'Eclairage meeting in Beijing (2007). NRCC report 50464. NRC

Institute for Research in Construction, Montreal, Canada. See: <http://archive.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc50464/nrcc50464.pdf>

CIBSE. 2013. TM52: The limits of thermal comfort: avoiding overheating in European buildings.

Circadian House, Principles and Guidelines for Healthy Homes. (2013).

Commission Internationale de l'Eclairage (CIE). 2004/2009. Ocular lighting effects on human physiology and behaviour. (CIE 158:2004). Vienna, Austria: CIE.

Heschong, Lisa. 1979. Thermal Delight in Architecture, MIT Press

Hobday, R. 2010. Designing Houses for Health - A Review ([http://centrallobby.politicshome.com/fileadmin/epolitix/stakeholders/Designing\\_Houses\\_for\\_Health\\_JUNE\\_2010\\_final.pdf](http://centrallobby.politicshome.com/fileadmin/epolitix/stakeholders/Designing_Houses_for_Health_JUNE_2010_final.pdf))

Hobday RA, Dancer SJ. Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives. *J Hosp Infect* 2013;84:271-282.

Kaplan, R. 2001. The nature of the view from home: Psychological benefits. *Environment & Behavior*, 33(4), 507-542.

Kellert, S.R., Heerwagen, J. and Mador, M. 2008. Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life. John Wiley and Sons

Van Marken, Lichtenbelt WD and Kingma BR, 2013. Building and occupant energetics: a physiological hypothesis. *Architectural Science Review*, Vol. 56, Issue 1, 2013.

Veitch, J.A., and Galasiu, A.D. The physiological and psychological effects of windows, daylight, and view at home: Review and research agenda. In. Ottawa, ON: NRC Institute for Research in Construction, 2012.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38(7), 743-757.

Wirz-Justice, A., Graw, P., Krauchi, K., Sarrafzadeh, A., English, J., Arendt, J., et al. (1996). 'Natural' light treatment of seasonal affective disorder. *Journal of Affective Disorders*, 37(2-3), 109-120.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Comfort in Patient Room of Healthcare Facilities in Tropical Region: A different requirement between patient and their companion

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**Abstract:** Comfort in a patient room directly involves with IEQ parameters, however, it is difficult to optimise the comfort because its two distinct groups of occupant may have different variation in physical and individual needs. This research aims to clarify different comfort requirements of patient room occupants by conducting a comprehensive field measurement in two large-scale hospitals in Bangkok, involving 89 occupants in 53 patient rooms. Data analysis was based on identifying the different comfort for patients and their companions by comparing the objective measurements according to comfort criteria of the established standard and the subjective comfort votes. The results showed that patients and companions perceived the room environment differently. Patients generally declared for a neutral perception and tended to prefer a slightly warmer thermal environment. Regarding thermal comfort evaluations, there was a notable discrepancy between PMV prediction and ASV results, especially for the companions. For an optimal comfort in a patient room, this research suggested a temperature range of 23.1 to 26.5°C. Beyond the thermal comfort parameter, this research also highlighted that indoor air quality is another key indicator for the overall comfort of patients, while acoustic environment plays more important role for companions.

**Keywords:** Indoor environmental quality, Thermal comfort, Patient room, Healthcare facility, Tropical region

### Introduction

It is commonly found in the Asian culture with a strong family values that patients always be accompanied by other people such as a partner and relatives during their visits to a hospital. In Thailand, for example, the number of accompanying rate raised up to 95.1% for inpatients, which is accounted for an overnight stay. Despite providing supports to patient, this companionship involves an indoor environmental issue in optimising thermal environment and comfort in hospital, particularly in a patient room, because of their distinct variation in physical health and individual needs.

There are a number of evidence that indoor environment has an impact on healthcare occupants; because the indoor environmental quality (IEQ) involve not only a health risk and safety, but also healing process of patient (Ulrich et al, 2004). The thermal environment is also an important factor for the occupants' comfort as well as symptoms of their health conditions; including dry, itchy skin, and thirst (Hashiguchi et al, 2005). A comfortable thermal environment also benefits to balancing the moods and facilitating healing in patients (Hwang et al, 2007). For an evaluation of thermal comfort in patient rooms, a number of studies had conducted a comparison results between patients and staff by using ASHRAE Standard 55 methodology and ISO7730 based on Fanger's predicted mean vote

(PMV) model. However, a prediction for thermal comfort according to this model is confined to healthy adults with more than 15 minutes occupancy in a temperate climate. Additionally, an attention is drawn to thermal comfort for people with special requirements. ISO/TS 14415 stated that people with special requirements are more sensitive to thermal conditions, and the ‘normal’ condition that provide comfort for healthy occupants may not be acceptable to people with disabilities.

Many previous studies conducted a field research that suggested a wide variation of findings concerning thermal comfort of patient in a temperate climate, as well as a sub-tropic and Asian context. Those variation in findings demonstrate that a consideration of individual requirements can be more critical than for person in a good health. However, the data related to the occupants’ comfort in a patient room is still very limited, and there is a need for a furthur research extended to different contexts. In a tropical region, the thermal comfort in a patient room seems to be neglected. A few study about thermal comfort of healthcare occupants found in the scientific literature mainly focused on staff’s comfort in Malaysian hospital. Therefore, this research focuses on the comfort requirements for patient and companion in a patient room of healthcare facility in a tropical region.

## **Research methods**

To clarify the comfort requirements of patient and companion in a patient room, the research framework covered objective measurments on the actual IEQ, including thermal environment conditions, and a subjective occupant satisfaction survey. The empirical data were collected during July 2015 to May 2016, at 53 patient rooms of 5 different wards in two large-scale general hospitals located in a rather hot-humid urban climate of Bangkok, Thailand. All cases reflect all-in-one hospital building with the generic physical environment of a single bed patient room, which is commonly depended on air conditioning system.

### ***Objective measurements for IEQ***

This study conducted an automated measurement of the air temperature, relative humidity, CO<sub>2</sub> concentration, sound level and illuminance by installing indoor climate sensors in 6 patient rooms. All of the devices were set for 10-min recording intervals and were installed approximately 1.0 m above floor level. Additionally, during the occupants’ survey in 53 patient rooms, indoor environmental conditions around each interviewee, including a globe temperature and wind velocity, were simultaneously recorded every one minute throughout the survey period or at least 30 mins in each room.

For thermal comfort assessment, the mean radiant temperatures were calculated according to the equation in ISO 7726. A metabolic rate and clothing insulation were estimated from subjects’ clothing and their activities at the time of interview. The metabolic rate was determined according to the metabolic rates for typical tasks in ASHRAE 55-2013. Clothing insulation values were derived by applying the equation from ISO 9920. The bedding ensemble that comprises of a single bed, mattress, sheets, and blanket was taking into account in this research because the total insulation resistance of bedding highly affects thermal comfort for a resting patient with a reclining posture (Lin and Deng, 2008).

The occupant surveys on environmental sensation and satisfaction was done by using a semi-structured interview following the questionnaire. The procedure took approximately 15-20 mins per participant. A total of 89 IPD occupants of different wards were invited to participate in this survey. This research focused on in-patients who admitted and stayed in the hospital for at least one night. With a limited accessibility, half of patients that involved

in this study were in a maternity ward, while patients in the wards of gastroenterology, oncology and general medicine were around 10 % equally. About 78 % of the in-patients were female, and the rest were male, whereas the female companions was 56 %. More detailed information of respondents involved in this study are in Table 1.

### ***Occupant sensation and satisfactions surveys***

Table 1. Information of respondents.

		Age N=89	Length of stay* [year]	Temperature [°C Ta]	Relative Air Velocity [m/s]	Relative Humidity [%]	Clothing Insulation [Clo]	Metabolic rate [met]
In-patient	41	17	4d 5h 59m	min	21.7	0.03	50	1.02
		42		avg	24.9	0.16	62	1.20
		80		max	27.7	0.31	77	1.41
Companion	48	19	5d 5h 21m	min	21.9	0.07	50	0.41
		47		avg	24.8	0.16	63	0.54
		76		max	27.7	0.32	77	0.82

\*average data only

The questionnaire used for both patients and companions comprised two main sections. The first section included the question related to background information of respondents. The second part asked about occupants' perception of and satisfaction with the IEQ in a patient room, including thermal comfort (temperature and humidity), illuminance, acoustic and indoor air quality (IAQ). Participants were asked to express their perception of the indoor environment on a 7-point scale based on the ASHRAE thermal sensation scale. The questionnaire also involved their overall satisfaction with environmental comfort in the department as well as its acceptability and their expectations.

### **Finding and discussion**

#### ***Indoor environment of a patient room in Thai hospitals***

The actual IEQ performance in a patient room of the case study hospitals was summarised in Table 2 and evaluated by comparing to a comfort criteria for hospital environments by the established standards; including the Guidelines for Design and Construction of Hospital and Health Care Facilities by the American Institute of Architects Academy of Architecture for Health (AIA) and the Facility Guidelines Institute (FGI), and the Standard for Environment Sanitation and Safety in Hospitals introduced by the Department of Health Service Support, Ministry of Public Health, Thailand.

Table 2. IEQ conditions of a patient room in the case study hospitals.

	Thermal Comfort		Lighting [lux]	Acoustic [dBA]	CO <sub>2</sub> concentration [ppm]	Air velocity [m/s]
	Temperature [°C Ta]	Relative Humidity [%]				
H1	Range	20.7 - 30.8	41 - 88	18 - 657	49.7 - 72.3	0.10 - 0.45
	Average	26.5	61	168	58.0	0.28
H2	Range	20.4 - 31.2	39 - 84	49 - 663	44.0 - 70.9	0.09 - 0.32
	Average	25.6	64	171	53.1	0.19

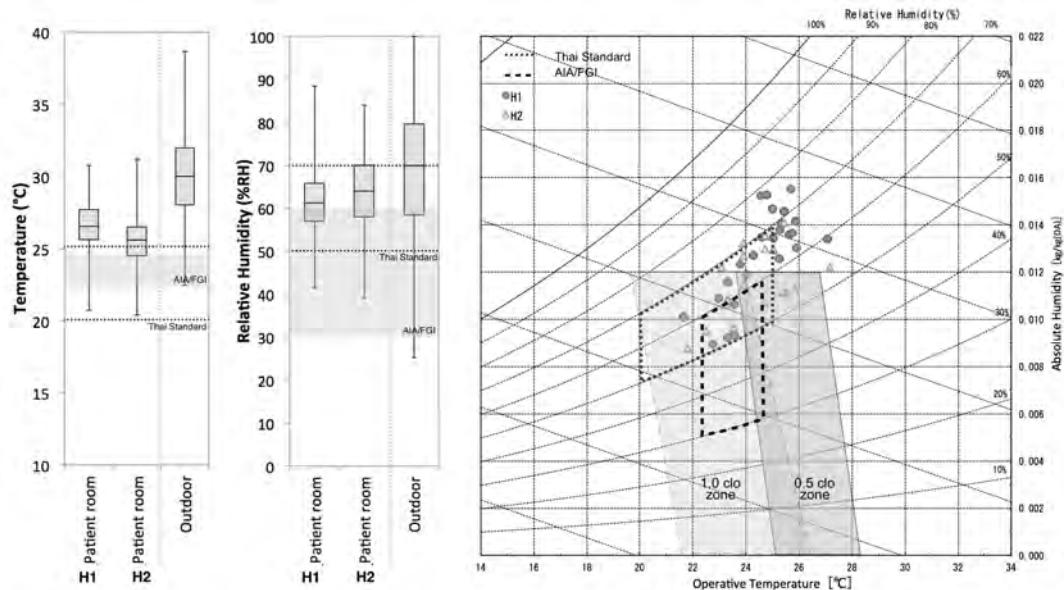


Figure 1. Indoor thermal environments in a patient room on the comfort chart of ASHRAE55-2013 Standard

### *Thermal Environment*

Air temperature in patient rooms of both case study hospital was almost identical in a range. However, it can be seen from Figure 1 that the average air temperatures were far above the upper limit of Thai standard and AIA/FGI. More than 55 % of all investigated data failed to meet the Thai standard and AIA/FGI. The reason for a failure to comply with AIA/FGI is also because of the high humidity. Moreover, more than 90 and 70 % of the results from both hospitals were outside of the summer comfort zone for healthcare occupants wearing ordinary summer clothing (0.5 clo) recommended by ASHRAE 55-2013 (Figure 1). The main reason for this involves not only high temperatures, but also high and unstable humidity. This results indicated the issue concerning temperature setting and humidity control of a patient room in a hot-humid region

### *Illuminance*

Similar to the international standards, a lighting condition in patient room recommended by the Thai standard is at 100 lx. About 25 % of measurements complied with the recommendation. The average illuminance was 168 to 171 lx, and nearly 15 % were brighter than 300 lx. Some fluctuation and unstable distribution of lighting were found. The natural lighting was having a role because all of the patient rooms are fitted with a large glass window and a single layer adjustable curtain. However, a problem concerning the solar heat gains through this opening was reported.

### *Acoustic environment*

According to the Thai standard, an acoustic condition suggested for a patient room should range between 40 to 45 dBA. However, the result indicated that less than 5% of the actual measurements were in the recommended range of sound. Although the average acoustic level in patient rooms was around 53 - 58 dBA, up to 30 % of data from H1 and 15 % from H2 were louder than 60 dBA.

### *Indoor air quality (IAQ)*

The level of CO<sub>2</sub> concentration is measured as an indicator for IAQ. The result shows the average CO<sub>2</sub> level in a patient room of IPD at 847 and 594 ppm for H1 and H2 respectively. Almost 98 % of CO<sub>2</sub> level from H2 were controlled under 1,000 ppm. Whereas, nearly 30 %

of the measurements in H1 were exceed the acceptable level of CO<sub>2</sub> at 1,000 ppm, and occasionally reached more than 2,500 ppm during a ward round.

#### Air velocity

In the case study hospitals, 22 % of measurements were in accordance with the Thai standard (0.08 - 0.12 m/s or 15 - 25 fpm), and almost 40 % not higher than 0.2 m/s. About 25 % of an average air speeds in the investigated patient rooms were greater than 0.2 m/s (40 fpm) which can increase the lower and upper operative temperature limit for the comfort zone.

#### **Thermal comfort of different occupants in a patient room**

Although the study on thermal environment in Swedish hospital pointed out that there was not much difference between patient and staff perceptions in summer (Skoog et al, 2005), the field measurements in Taiwanese and Japanese hospitals indicated that physical conditions of an occupant affected a response on thermal sensation and a perceive to the thermal environment (Hwang et al, 2007; Hashiguchi et al, 2008). The study on thermal environment in a patient room of a Belgian healthcare facility also revealed that the mean PMV of patients with neurological treatments was notably different from healthy users (Verheyen et al, 2011). Similarly, another study on thermal sensation of Italian patients pointed out that the patients' comfort were around neutrality while the medical staff pointed toward warmer sensation (Ferraro et al, 2015).

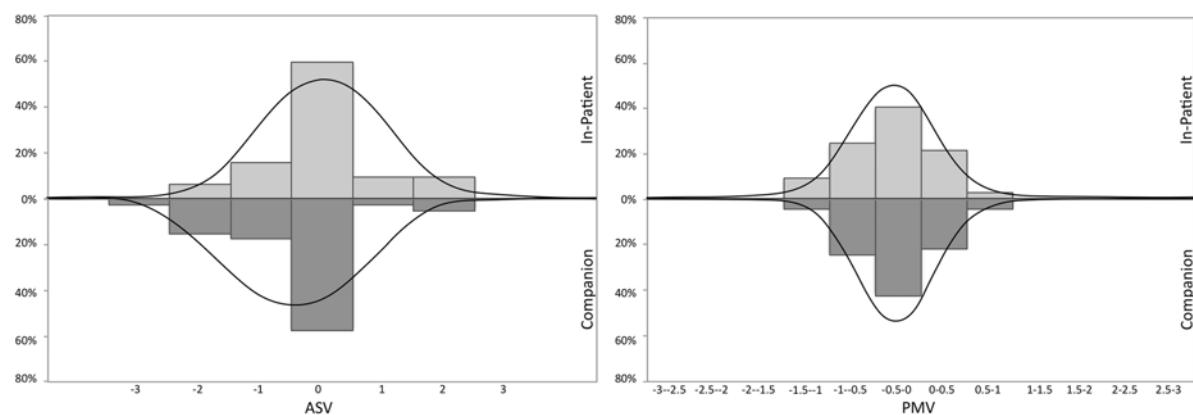


Figure 2. Percentage frequency of thermal sensation vote (ASV & PMV) by each group of occupants

As the thermal comfort of in-patient can be different from a healthy companion, this research separately analysed the data of in-patients and companions in order to clarify the difference. As shown in Figure 2, the PMV results for in-patients and companions produced uniform graphs of distribution whereas the results based on the actual sensation vote (ASV) illustrated the different thermal sensation between in-patients and companions. The distribution of ASV results for the companions concentrated at slightly colder than neutrality (ASV between -1 and 0). It can be a case that the illness and medical treatments may decrease an ability to remain cognitively aware of their surrounding environment.

Furthermore, this study found a strong relationship between the PMV and ASV data for in-patients whereas the results for companions did not reach the significant level (Figure 3). However, the regression plot indicated that the prediction fails to give the accurate information on their thermal sensations. A neutrality (PMV=0) for patient was shifted to 0.14 scale points of the ASV and to -0.37 for the companions. This discrepancy between PMV and ASV poses a problem in deciding the appropriate thermal comfort, particularly in term of the temperature, in a healthcare building in a tropical region.

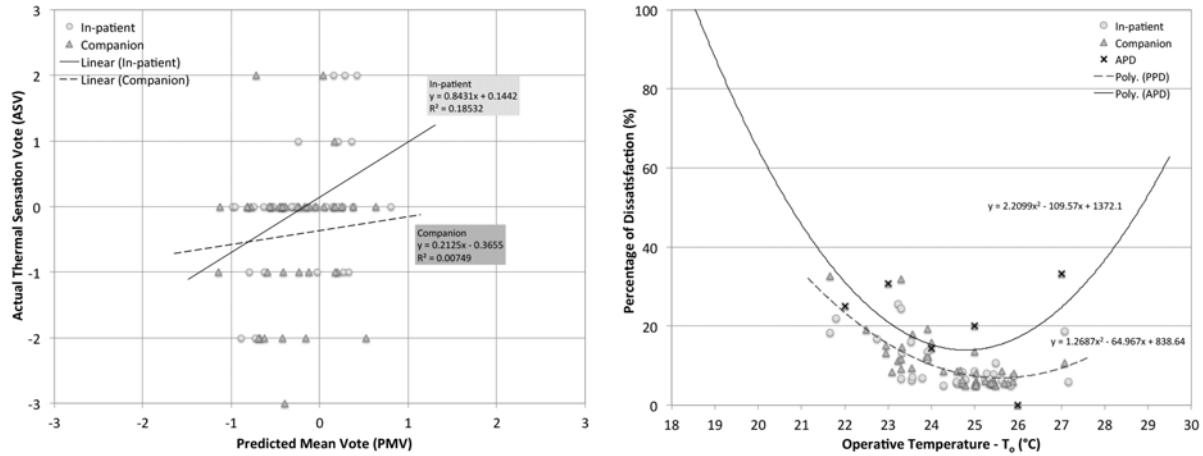


Figure 3. Correlation between PMV & ASV (left), and the comparison of PPD & APD (right)

To reconcile such different neutrality, this research suggested for a common range of temperature by a correlation analysis between the predicted percentage of dissatisfied (PPD) and operative temperature based on the theoretical calculation of the PMV and the actual percentage of dissatisfied (APD) with the operative temperature ( $T_o$ ). The acceptable temperature range for thermal comfort of both occupant groups in a patient room was calculated at 20 % of PPD according to ASHRAE Standard 55. Regarding to a study in Taiwan hospital, the range of temperature for the comfort zone by 20 % of dissatisfaction was suggested between 21.8 - 26.2 °C for summer (Hwang et al, 2007). Figures 3 also shows that the temperature range based on the observed APD, 23.1 - 26.5°C, was narrower and the lower range was slightly warmer than that one from the PPD prediction which being 22.8 - 28.3 °C. The values of calculated PPD for companions was higher than those of in-patients although their direct votes for thermal comfort satisfaction was greater than 95 %. The difference of comfort satisfaction between in-patients and companions was less than 5 %, however, 88 % of in-patients preferred no change of the indoor environment. In addition, in-patients tend to prefer slightly warmer thermal environment than their companions who are satisfied at lower temperature.

#### ***Occupants perception and satisfactions on IEQ in a patient room***

Although thermal comfort parameter can be one of the good indicator for the comfort requirement, it can be false or underestimate for patients who are in a frail condition. The results from occupant satisfaction surveys shows that more than 68 % of in-patients felt better than neutral in their patient room environments, which was greater than the companions.

Focusing on five major IEQ parameters, more than 50 % in-patients perceived the indoor air temperature, humidity, illuminance and acoustic conditions as neutral. About 31 % of in-patient reported on un-fresh and stuffy air quality. Whereas, the companion mostly indicated uncomfortable condition concerning overall environment, the acoustic condition in particular. The results lead to the understanding that in-patients could accept the environmental conditions with a lower expectation even though their sensation votes were outside of the three recommended comfort criteria. However, in-patients are influenced by their health conditions and medical treatments, and their attitudes that is given a medical treatment activities as the highest priority. They may not found themselves in the best of comfort state. To accurately evaluate the patient comfort, this study then addressed on the extended parameter beyond thermal comfort factor.

Table 3. Correlations between overall comfort satisfaction and IEQ parameters.

	Overall Comfort Satisfaction	Thermal Comfort		Lighting	Acoustic	IAQ
		Temperature	Humidity			
In-patient	Person Correlation Sig. (1-tailed)	1 .037 .410	-.040 .403	.074 .323	.223 .081	.458** .001
Companion	Person Correlation Sig. (1-tailed)	1 .166 .129	-.018 .451	.337** .010	.414** .002	.149 .156

\*\*. Correlation is significant at the 0.01 level (1-tailed).

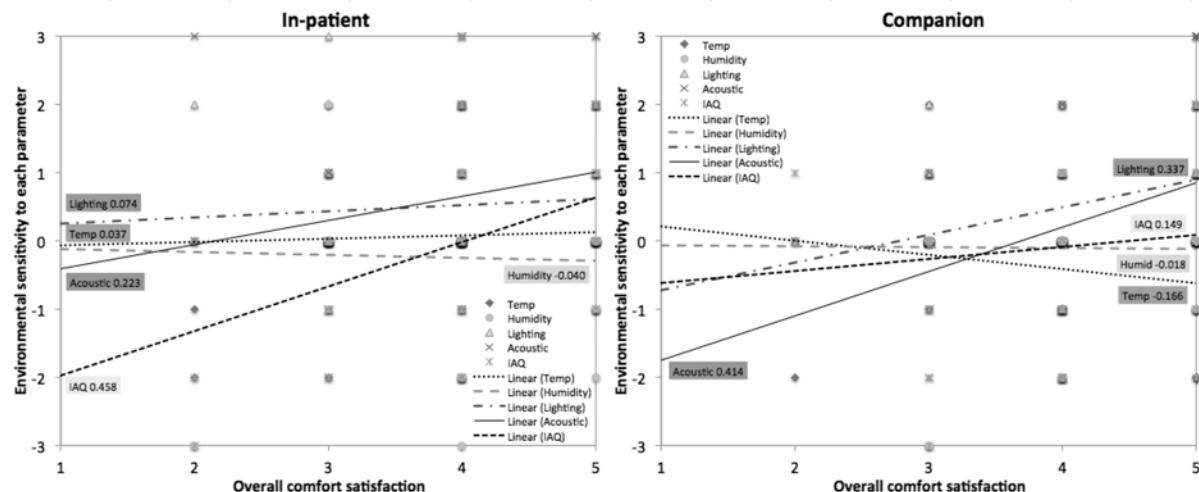


Figure 4. Correlations between comfort satisfaction and IEQ sensitivity of in-patient and companion

Regarding a pearson correlation analysis between overall comfort and the major IEQ parameters, the results indicated that indoor air quality is significantly related to the overall satisfaction of indoor environmental comfort for in-patient ( $p < 0.01$ ), while acoustic and lighting plays more important role for the companions (Table 3). To validate the result, this study ran a regression analysis of those significant parameters, the coefficient for IAQ parameter was statically significant ( $p < 0.01$ ). The result indicated that for every unit increase in IAQ perception, about 0.32 unit of overall environment satisfaction for in-patient can be expected to increase. For the companions, the coefficient of acoustic conditions was significant at  $p < 0.01$  while the factor of illuminance was not reach a significant level. This result suggested that the overall comfort satisfaction of the companions can be expected to increase by 0.22 unit for every unit increase in an acoustic perception. As the results, this study provided a clear evidence to confirm that there was a combined effect of thermal environment with other IEQ conditions that constitute the comfort of occupants in a patient room. A perception on IAQ is one of the important indicator for overall environmental comfort satisfaction of in-patients, and acoustic environment is another key for the companions' comfort.

## Conclusion

This study clearly verified the specific requirements for the thermal comfort of in-patients and their companions which is significant for enhancing the optimal comfort and health in a patient room in a hot-humid region. The measurement results indicated that in-patients could accept their patient room environment although the thermal condition therein failed to comply with the Thai standard and AIA/FGI, as well as the summer comfort zone of

ASHRAE standard 55. The main reason of failure involves high temperatures, and highly unstable humidity. This study highlighted that in-patients differently perceived the thermal environment from the healthy companions. While in-patients tend to prefer slightly warmer thermal environment, the companions are satisfied at lower temperature. In addition, to achieve 80 % of satisfaction, the temperature range for comfort in a patient room is suggested between 23.1 to 26.5 °C based on the observed APD. The established standard for thermal environment in a patient room should be revised by shifting to a warmer temperature range, which will benefit to occupants comfort and energy saving on air conditioning as well.

Furthermore, this study also addressed that the comfort of occupants in a patient room constitutes of a combined effect between thermal environment and other IEQ parameters. A perceived IAQ is one of the important indicator for the overall comfort of inpatients, while acoustic environment is another key for the companions' comfort. As there is an integration of parameters that determine the comfort of human body, not an environmental component alone; the true effects of thermal conditions on a patient comfort can easily be misleading. For an accurate evaluation of patient comfort, a further study on the influence of disease and medical treatment on thermal comfort in patients is necessary.

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### References

- Ferraro, S.D., Iavicoli, S., Russo, S., and Molinaro, V. (2015). A field study on thermal comfort in an Italian hospital considering differences in gender and age. *Applied Ergonomics*, 50, pp.177-184.
- Hashiguchi, N., Hirakawa, M., Tochihara, Y., Kaji, Y., and Karaki, C. (2005). Thermal environment and subjective responses of patients and staff in a hospital during winter. *Journal of Physiological Anthropology and Applied Human Science*, 24, pp.111-115.
- Hashiguchi, N., Hirakawa, M., Tochihara, Y., Kaji, Y., and Karaki, C. (2008). Effects of setting up of humidifiers on thermal conditions and subjective responses of patients and staff in a hospital during winter. *Applied Ergonomics*, 39, pp.158-165.
- Hwang, R.L., Lin, T., Cheng, M., and Chien, J. (2007). Patient thermal comfort requirement for hospital environments in Taiwan. *Building and Environment*, 42, pp.2980–2987.
- Lin, Z., and Deng, S. (2008). A study on the thermal comfort in sleeping environments in the subtropics: Measuring the total insulation values for the bedding systems commonly used in the subtropics. *Building and Environment* 43, pp.905–916.
- Skoog, J., Fransson, N., and Jagemar, L. (2005). Thermal environment in Swedish hospitals: Summer and winter measurements. *Energy and Buildings*, 37, pp.872-877.
- Ulrich, R., Quan, X., Zimring, C., Joseph, A., and Choudhary, R. (2004). The role of the physical environment in the hospital of the 21st century: A once-in-a-lifetime opportunity. In: Report to the Center for Health Design for the Designing the 21st Century Hospital Project, Robert Wood Johnson Foundation.
- Verheyen, J., Theys, N., Allonsius, L., and Descamps, F. (2011). Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility. *Building and Environment*, 46, pp.1195-1204



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## Regional specificity of thermal comfort perception – a critique of the RP-884 dataset through an analysis of The Pakistan Project

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**Abstract:** The extensive database of thermal comfort field studies collated and standardised in the ASHRAE RP-884 has provided the basis on which predictive formulae for indoor comfortable conditions are developed. These formulae vary minimally between geographic and climatic regions intimating a singular, uniform relationship between prevalent outdoor conditions and indoor desirable (comfortable) conditions. The *adaptive theory* suggests acclimatization and behavioural adaption account for the acceptance of a range of environmental conditions that would otherwise be considered uncomfortable, thus legitimising the use of a predictive formula that is defined climatically but does not cater to regional and cultural variations in thermal perception. This research seeks to critique the use of a single predictive formula for populations resident in similar climatic conditions, yet exposed to different regional and cultural influences. To this end, a comparison of predictive formulae developed through the Pakistan Project of the RP-884 dataset and its component field study sites is undertaken to assess the regional specificity of thermal comfort perception. The adaptive formula is further critiqued through an analysis of different outdoor reference temperatures by which indoor comfort is determined. A case is thus made for the formulation of indoor thermal comfort guidelines within the climatic and cultural context where they are to be applied.

**Keywords:** Thermal comfort; Thermal perception; RP-884; Adaptive theory; Pakistan Project

### Introduction

Thermal comfort has been defined as ‘that condition of the mind that expresses satisfaction with the thermal environment’ (ASHRAE/ISO 7730), as such thermal comfort is not a steady-state entity rather it is a subjective assessment of the environmental conditions that is influenced by the perceptions and expectations of each individual. It is thus acknowledged to be a uniquely personal measure of both the physiological and psychological satisfaction one feels within the environment (Fountain et al. 1996; Hensen 1991; Nicol et al. 2012).

Two methodological formats have dominated research into thermal comfort, the deterministic lab-based *steady-state methodology* which has underpinned most of the established comfort standards the world over, and the holistic person-environment centric *field-study methodology* (de Dear 2004; Nicol et al. 2012). The steady-state studies have been successful in providing a solid foundation of thermal comfort knowledge, however the lack of contextual (location, outdoor climatic conditions) and psychological influences (based on previous experiences and expectations) within it has led to dissatisfaction with the steady state model (de Dear & Brager 1998; Brager & Dear 1998; Fountain et al. 1996). Field study methodology is on the other hand rooted in context (climatic, social and psychological) providing a largely unadulterated representation of the environmental

conditions that provide comfort to an individual and also of the various methods of adaption (of the environment and of self) employed in order to maintain thermal comfort.

The empirical observations of thermal comfort perception collected through field study methodology have given rise to *the adaptive theory* which recognises that when a change in environmental conditions produces discomfort, people react in ways so as to restore their comfort (Nicol et al. 2012). The control over both the personal and environmental parameters (as occurs in unconditioned buildings) has led to the understanding that people are more accepting of a wide range of environmental conditions if they are able to modify their environment (Brager & de Dear 1998). As a consequence the comfort standards advising design and informing legislation towards comfortable indoor conditions developed through the adaptive model recommend a wider range of acceptable thermal comfort parameters than those developed from steady state studies, particularly in naturally ventilated buildings.

The current understanding of contextual thermal comfort including the formulation of the adaptive model is largely due to the development of comprehensive databases where existing field studies were compiled and collated enabling systematic reviews and meta-analysis. These databases include those compiled by Humphreys (1975, 1978), and De Dear and Auliciems (1988), the European Smart Control and Thermal Comfort (SCATS) (Mccartney & Nicol, 2002), and the ASHRAE commissioned RP-884 (de Dear & Brager 2002). The adaptive model has provided a link between indoor comfort parameters and outdoor prevalent conditions with the meta-analysis of the datasets providing predictive formulae expounding these relationships.

The reference temperature used in these predictive formulae varies between the use of the outdoor monthly mean air temperature (ASHRAE), the running mean outdoor air temperature (EN15251) and the weighted mean running outdoor temperature (Humphreys).

The strength of the predictive formulae depend on the accuracy of the relationship between the reference temperature used and the indoor comfortable temperature during data collection, however in practice, concurrent outdoor conditions have rarely been a part of data collected during field studies. Consequently the outdoor data used in analysis has typically been sourced from historic data which often varies in granularity with respect to its temporal and spatial quality. Additionally the datasets comprise of data collected in climatically diverse regions and across different seasons. The formulae developed from these datasets thus predict a wide range of comfort temperatures which proponents of the adaptive theory suggest is within acceptable limits of comfort due to acclimatization and behavioural adjustments, however the comfort standards developed from these datasets are deemed successful if 80% of the population reports satisfaction with these predicted conditions (de Dear 2004; de Dear & Brager 2002; Nicol et al. 2012).

### **Lines of enquiry**

The adaptive predictive formulae are often reflective of the difference in thermal comfort parameters for different seasons within a region, attributing such variations to acclimatization and expectation. In hot-dry climates however there is often a large diurnal change in temperature which has a significant effect on lifestyle including the passive cooling of indoor climates (i.e. opening of windows during the cooler night and closing them during the hottest part of the day) (Nicol et al. 2012) yet the reference temperatures currently used in the adaptive equations are not sensitive to these daily fluctuations.

This paper hypothesizes an improvement in the predictive accuracy of adaptive formula that are developed with more sensitivity to immediate changes in outdoor temperature. Furthering on the notion of thermal comfort being a regionally specific entity, it is the contention of this paper that adaptive formulae (and standards) developed for a specific geographic region within a singular climatic classification, will provide indoor conditions that are acceptable for a significantly higher percentage of the population than from those developed from a composite dataset.

This is undertaken through the analysis of a sub-set of the world database of thermal comfort field studies, the RP-884, specifically, The Pakistan Project.

The RP-884 is a composite dataset that comprises 21000 readings collected from 160 buildings from a diverse climatic and culturally varied region that extended over 4 continents (fig. 1) and from which the adaptive formula (eq. 1) has been developed (de Dear & Brager 1998). The RP-884 dataset was divided according to climatic classification and analysed by Toe & Kubota (2013) to develop adaptive equations for each (eq. 2-4).

The Pakistan Project refers to a thermal comfort field study of 5 cities located within the country of Pakistan, undertaken by Oxford Brookes University in 1994-95 and that was conducted to assist in the development of thermal comfort standards for the country. The dataset comprises of 4783 readings collected from a rather limited sample set of 36 individual survey participants located in 5 geographically, climatically, and culturally differing urban centres: Multan, Peshawar, Quetta, Saidu Sharif and Karachi. The consequent analysis included the development of adaptive formulae (eq. 5 and 6) (Nicol et al. 1994).

$$\begin{aligned} T_{\text{comf}} &= 17.8 + 0.31T_{\text{mmout}} & - & \text{ (equation 1)} \\ T_{\text{comf}} &= 13.8 + 0.57T_{\text{outdm}} & \text{(hot-humid)} & - \text{ (equation 2)} \\ T_{\text{comf}} &= 13.7 + 0.58T_{\text{outdm}} & \text{(hot-dry)} & - \text{ (equation 3)} \\ T_{\text{comf}} &= 18.6 + 0.22T_{\text{outdm}} & \text{(moderate)} & - \text{ (equation 4)} \end{aligned}$$

Where  $T_{\text{comf}}$  is the indoor comfort temperature,  $T_{\text{mmout}}$  is the monthly mean outdoor dry bulb temperature and  $T_{\text{outdm}}$  is the daily mean outdoor temperature

$$\begin{aligned} T_{\text{comf}} &= 12.1 + 0.534T_o & \text{(for summer; } T_o > 20^\circ\text{C)} & - \text{ (equation 5)} \\ T_{\text{comf}} &= 14.5 + 0.534T_o & \text{(for winter; } T_o < 20^\circ\text{C)} & - \text{ (equation 6)} \end{aligned}$$

Where  $T_o$  is the mean maximum temperature and the mean minimum temperature for the month and climatic zone concerned (Nicol et al. 1994)

The field studies comprising the hot-dry climate as classified by Toe & Kubota and represented in equation 3 are those undertaken in the Pakistan project sites of Multan, Peshawar, Quetta, and Saidu Sharif in the summer season, Karachi in both summer and winter seasons, and also include the Greek city of Athens in the summer season.

Of these field study sites, Athens and Karachi are both coastal cities and as such are climatically different from land-locked urban regions; coastal climates have fewer extremes of temperature between the different seasons and are often characterised by diurnal directional winds. The inclusion of these two coastal cities in the hot-dry climatic classification thus appears erroneous, and any analysis of the dataset undertaken will be compromised as it is representative of a broader climatic range than specified.

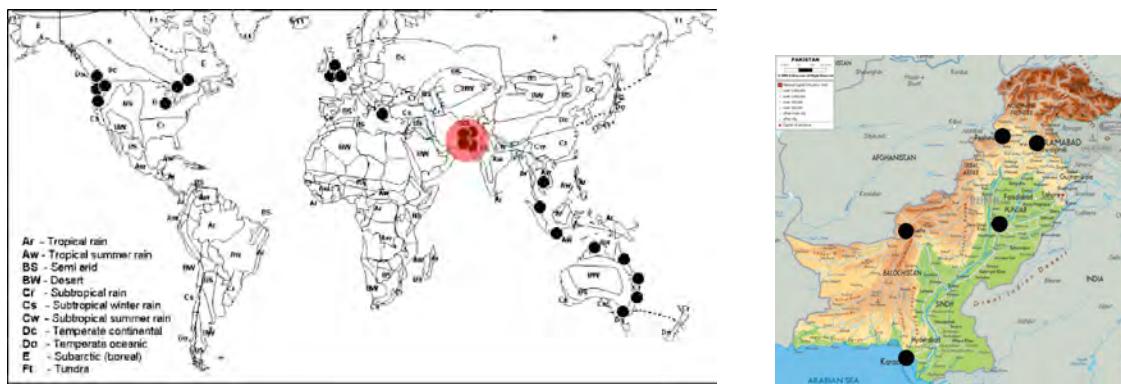


Figure 1. World map indicating extent of initial field study sites comprising RP-884 and indication of primary climatic classification of each region (de Dear & Brager 2002) and relief map of Pakistan with indicators for RP-884 *The Pakistan Project* field study sites. (RP-884 site location indicated by solid black circle, Location of Pakistan highlighted by red circle). Note large variation in geographic and consequent climatic characteristics of field study sites included in datasets.

In order to develop a precise adaptive formula of hot-dry climatic conditions the two coastal cities, Karachi and Athens, have been excluded from the dataset and a new adaptive formula developed as shown in equation 7. This formula predicts a comfort temperature range higher yet narrower than the previous variation (eq. 3) indicating an increased accuracy due to the restrictions in the dataset.

$$T_{\text{comf}} = 22.51 + 0.22T_{\text{outdm}} \quad - \quad (\text{equation 7})$$

This is the adaptive formula against which further analysis within this paper is undertaken and references hot-dry climatic conditions within the Pakistan Project of the RP-884.

It should be noted that the data collected from the field study site of Saidu Sharif is included in the dataset, however the geographic location of the city with regard to its altitude, and its short summer season that has an average high of 36.8°C which is considerably lower than the summer high temperatures recorded for the other cities within the dataset, leads rise to concerns that the cities' population does not experience the same variations in climatic conditions and will therefore have different thermal comfort preferences to the residents of other cities within the dataset. This difference may reflect in the results of the analysis.

### **Outdoor reference temperatures for adaptive equations**

It is generally understood that the accuracy of the predictive formulae is dependent on the strength of the relationship between the indoor comfort temperature and the outdoor reference temperature. As indicated previously however, the thermal comfort field studies from which these formulae are developed have relied on historically available data of outdoor temperatures which often have a coarse granularity and weak geographic and temporal link with the recorded indoor temperature. In light of this limitation it is proposed that the existing formulae will more accurately predict indoor comfort conditions if the outdoor reference temperatures used are reflective of daily or immediate fluctuations.

In order to test this hypothesis, the predictive formulae developed for hot-dry climatic conditions (eq. 7) was used with three different outdoor reference temperatures and the resulting predicted indoor comfort temperatures compared to those empirically measured

for each city in the dataset. This was undertaken through a series of one-sample T-tests and the outdoor reference temperatures used were the outdoor maximum daily temperature, the outdoor daily mean temperature , and in the absence of an hourly outdoor temperature indicative of diurnal range, a 6am minimum temperature (used for readings taken during the cooler times of the day: 1am-to-11am) and a 3pm maximum temperature (used for readings during the hotter times of the day: 11am-to-1am).

When the maximum daily temperature is taken as outdoor reference temperature, a significant difference was found to exist between the predicted and empirical comfort temperatures in Multan [M=29.4, SD=1.38; t(12)=3.9, p=.002], Peshawar [M=29.54, SD=1.5; t(9)=3.64, p=.005] and Quetta [M=29.3, SD=1.06; t(9)=4.33, p=.001]. No significant difference is recorded for the city of Saidu Sharif.

A comparison of the empirical readings and the predicted means when the mean daily temperature is used provides significant differences between the two for the cities of Multan [M=29.74. SD=1.58; t(14)=2.8, p=.014] and Peshawar [M=30.4, SD=1.79; t(18)=4.4, p=.000] while the result is for Quetta is non-significant at p=.061. No significant difference is recorded for Saidu Sharif.

While using an outdoor reference temperature that is reflective of the diurnal variations in outdoor climate temperature no significant difference between predicted and empirically measured comfort temperature was recorded for all 4 cities: Multan, Peshawar, Quetta, and Saidu Sharif.

This analysis shows that the predictive value of the adaptive equation is most accurate through the use of an outdoor reference temperature that is reflective of diurnal variations in climate. This lays the groundwork toward the development of adaptive formulae with greater predictive accuracy through the use of an outdoor reference temperature that reflects hourly variations.

On this basis, the adaptive equation for the hot-dry climatic classification through the Pakistan Project of the RP-884 dataset (eq.7) can be modified to:

$$T_{\text{comf}} = 22.51 + 0.22T_{\text{outdiurnal}} \quad - \quad (\text{equation 8})$$

Where  $T_{\text{comf}}$  is indoor comfort temperature and  $T_{\text{outdiurnal}}$  is the outdoor temperature representative of diurnal variation, ideally being hourly outdoor temperature, lacking which, most recently available temperature reflective of daily variations would suffice.

### **Regional specificity of adaptive equations**

Existing adaptive equations have been developed for use within regions which have similar climatic classification, however such regions include populations from diverse cultural backgrounds and consequently have differing thermal expectations. In order to determine the accuracy of such adaptive equations in predicting the thermal preferences of a culturally diverse population, an analysis of the parts of a composite mono-climatic dataset: the hot-dry climatic region of the Pakistan Project (as outlined above) is undertaken. Adaptive equations are developed for each culturally specific region (field study sites) and their applicability in predicting thermal comfort for other similarly climatically classified sites within the dataset is assessed.

The Pakistan Project dataset is divided into its composite cities: Multan, Peshawar, Quetta and Saidu Sharif and individual adaptive equations developed for each (eq. 9-12). The predicted thermal comfort for each of these cities is compared to the empirical data of the other cities to determine if a statistical difference exists in the thermal comfort results

achieved from the adaptive formula and the empirical readings obtained from the field surveys.

$$T_{\text{comf}} = 19.54 + 0.34T_{\text{outdm}}$$

$$T_{\text{comf}} = 23.91 + 0.18T_{\text{outdm}}$$

$$T_{\text{comf}} = 25.49 + 0.12T_{\text{outdm}}$$

$$T_{\text{comf}} = 20.64 + 0.27T_{\text{outdm}}$$

	Multan	-	(equation 9)
	Peshawar	-	(equation 10)
	Quetta	-	(equation 11)
	Saidu Sharif	-	(equation 12)

A series of single-sample T-tests were conducted which show no significant difference between the predicted thermal comfort values of the cities (Multan, Peshawar, Quetta and Saidu Sharif) with the empirical data of the other cities. This indicates that that a single adaptive formula should provide accurate prediction of indoor comfort temperatures for the entire region. However as the adaptive theory recognises thermal comfort perception as a non-static entity that varies due to climatic and seasonal changes, further analysis was undertaken to determine if the adaptive equation(s) remain accurate throughout the entire range of outdoor temperature (a summary of which is represented in Table 1).

Table 1 Summary of single-sample T-test analysis of adaptive equations predicted mean and empirical data of various cities with similar climatic classification.

(Where Sig.= significant; Non-Sig.= non-significant; insuf.data = insufficient data)

City of which adaptive formula used (predicted mean)	City of which empirical dataset was compared											
	25°C - 30°C				30°C - 35°C				35°C - 40°C			
	Multan	Peshawar	Quetta	Saidu Sharif	Multan	Peshawar	Quetta	Saidu Sharif	Multan	Peshawar	Quetta	Saidu Sharif
Multan	-	Sig.	Insuf. data	Non Sig.	-	Sig.	Sig.	Non Sig.	-	Non Sig.	Insuf. data	Non Sig.
Peshawar	Sig.	-	Insuf. data	Non Sig.	Non Sig.	-	Non Sig.	Non Sig.	Insuf. data	-	Insuf. data	Non Sig.
Quetta	Sig.	Sig.	-	Non Sig.	Non Sig.	Non Sig.	-	Non Sig.	Insuf. data	Non Sig.	-	Non Sig.
Saidu Sharif	Sig.	Sig.	Insuf. data	-	Non Sig.	Sig.	Non Sig.	-	Insuf. data	Non Sig.	Insuf. data	-

The analysis of the Multan adaptive formula shows a significant difference in predicted mean and empirical data for the temperature range of 25°C - 30°C with the city of Peshawar [M=30.47, SD=1.03; t(5)=4.15, p=.009] while no significant difference was recorded for Saidu Sharif and insufficient data was available for Quetta. Between 30°C - 35°C a significant difference was reported for Peshawar [M=28.48, SD=1.38; t(3)=-3.3, p=.045] and Quetta [M=29.46, SD=.91; t(9)=-4.5, p=.001] while Saidu Sharif was not significantly different. In the 35°C- 40°C temperature range no significant difference was recorded for Peshawar and Saidu Sharif while there was insufficient data for analysis for Quetta.

The analysis of the adaptive formula of Peshawar showed a significant difference with the Multan empirical data in the 25°C - 30°C range [M=30, SD=.68; t(5)=4.6, p=.006], Saidu

Sharif was not significantly different and insufficient data was available for Quetta. No significant difference was recorded for Multan, Quetta and Saidu Sharif for the outdoor temperature range 30°C - 35°C, and for Saidu Sharif for the range of 35°C - 40°C while there was insufficient data for analysis for the cities of Multan and Quetta in this range.

The analysis of the Quetta adaptive formula in the range 25°C - 30°C shows a significant difference with the empirical data of Multan [ $M=30.05$ ,  $SD=.68$ ;  $t(5)=4.48$ ,  $p=.005$ ] and Peshawar [ $M=30.47$ ,  $SD=1.03$ ;  $t(5)=4.13$ ,  $p=.009$ ] while Saidu Sharif is not significantly different. No significant results are recorded for the outdoor temperature range 30°C - 35°C and 35°C - 40°C however Multan was not analysed due to insufficient data for this range.

The analysis of the predicted mean of Saidu Sharif for the temperature range of 25°C - 30°C reports a significant difference with empirical data of Multan [ $M=30.05$ ,  $SD=.68$ ;  $t(5)=7.63$ ,  $p=.001$ ] and Peshawar [ $M=30.47$ ,  $SD=1$ ;  $t(5)=6$ ,  $p=.002$ ] while there is insufficient data for analysis for Quetta. No significant differences are recorded for the cities Multan, Peshawar and Quetta in the outdoor temperature range 30°C - 35°C. The temperature range 35°C - 40°C the analysis shows no significant difference for the city of Peshawar while there is insufficient data for analysis of both Multan and Quetta.

This analysis reinforces the non-static quality of thermal comfort perception highlighting the variations in thermal comfort due to changes in outdoor temperature. The analysis also shows that the adaptive formulae developed from a particular regional population may not provide a wholly accurate prediction of thermal comfort temperatures for other populations with the same climatic classification.

The results of the analysis however are not fully comprehensive as the parts of empirical data of several field study sites was found to be insufficient for analysis.

## Conclusions

This paper hypothesizes that adaptive formulae that are regionally developed within the climatic and cultural environment in which they are to be applied will provide a more accurate prediction of thermal comfort preference for the local population than those developed through large databases of climatically diverse field studies such as ASHRAE's RP-884. The hypothesis was tested on a sub-set of the RP-884 (the Pakistan Project) focusing on the case studies that fall within hot climatic classification and within a single geographic region.

A thorough statistical analysis of the climatically and regionally appropriate adaptive equations developed from this dataset show that the predictive accuracy of the formulae increases when the outdoor reference temperature used is reflective of daily variations in outdoor conditions. These tests also indicate that the local populations of different regions within a climatic classification have varying perceptions of thermal comfort due to which the adaptive formula developed for a particular region may not be wholly applicable to other regions within the same climatic classification. These results thus reinforce the need for regionally developed adaptive formulae which incorporate a sensitivity to diurnal variations in temperature, and to the local climatic and cultural context.

It is pertinent to note that due to the limited available data for the development of regional adaptive formulae, there was in some instances insufficient data for analysis, however these have been highlighted within the results of the test (Table 1) and do not detract from the conclusions outlined. Furthermore, the focus of this investigation was on the case studies located in hot climatic regions which are also part of the developing world. It is uncertain if similar results would be achieved in developed world regions within

similarly classified climates. Additionally it should be noted that the results of this investigation may not be applicable in regions with cooler climates that are not subject to large diurnal differences in temperature, in such cases the use of an outdoor reference temperature such as daily or weekly mean temperature may provide reasonably accurate predictions of thermal comfort preference for the majority local population.

The research indicates that thermal comfort perception of a population is dependent upon the local climatic and cultural context and is thus regionally specific and shows the hypothesis holds true for hot climatic conditions in developing world regions. However further investigation is required for developed world regions and cooler climatic conditions.

## References

- ASHRAE, 2016. ASHRAE. Available at: <https://www.ashrae.org/> [Accessed September 21, 2016].
- Brager, G.S. & Dear, R.J. De, 1998. Thermal adaptation in the built environment : a literature review. *Energy and Buildings*, 17, pp.83–96.
- de Dear, R., 2004. Thermal comfort in practice. *Indoor air*, 14 (Suppl 7), pp.32–9. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/25076188>.
- de Dear, R. & Brager, G.S., 1998. Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions*, 104(1), pp.145–167.
- de Dear, R.J. & Auliciems, A., 1988. Airconditioning in Australia - II - User attitudes. *Architectural Science Review*, 31(September), pp.19–27.
- de Dear, R.J. & Brager, G.S., 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings*, 34(6), pp.549–561. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0378778802000051>.
- Fountain, M., Brager, G. & de Dear, R., 1996. Expectations of indoor climate control. *Energy and Buildings*, 24(3), pp.179–182. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0378778896009887>.
- Hensen, J.L.M., 1991. *On the thermal interaction of building structure and heating and ventilating system of building structure and heating and ventilating system*. Doctoral dissertation, Eindhoven University of Technology, (FAGO). ISBN 90-386-0081-X.
- Humphreys, M.A., 1975. Field Studies of Thermal Comfort Compared and Applied. In *Symposium on Physiological requirements of the microclimate*. Prague.
- Humphreys, M.A., 1978. Outdoor Temperatures and Comfort Indoors. *Building Research and Practice*, 6(2), pp.92–105.
- ISO, 2016. International Organization for Standardization. Available at: [www.iso.org](http://www.iso.org) [Accessed September 21, 2016].
- Mccartney, K.J. & Nicol, J.F., 2002. Developing an adaptive control algorithm for Europe *Energy and Buildings* 34, pp.623–635.
- Nicol, F., Humphreys, M. & Roaf, S., 2012. *Adaptive thermal comfort: principles and practice* 1st ed., London & New York: Routledge.
- Nicol, J.F., Gamy, G.N., Sykes, O., Humphreys M.A., Roaf, S., Hancock, M., 1994. *A survey of thermal comfort in Pakistan - toward new indoor temperature standards*. School of Architecture, Oxford Brookes University.
- Toe, D.H.C. & Kubota, T., 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database. *Frontiers of Architectural Research*, 2(3), pp.278–291. Available at: <http://dx.doi.org/10.1016/j foar.2013.06.003>.



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*Design to Thrive*

## Thermal Comfort in Homes of Social Interest Study

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**Abstract:** Research relates thermal comfort in homes of social interest in three different historical moments, specifically about the evolution of materials, scaling of rooms and openings (windows), indicating which variables are of greater influence on thermal comfort to the user. Today housing constructions prioritizes low cost, not allowing thermal comfort in each room, and it doesn't favor family life, which has a fundamental role in the promotion of human development and quality of life. The goal is to analyze and compare three houses of social interest, one-story houses, related to surrounding materials, variables of thermal comfort that comply with the ABNT 15220-3 standards with the specifications and construction guidelines, bioclimatic strategies for the whole national territory. For the choice of the object of study, the bibliographic survey identified three important moments in the development route of homes of social interest which are: the first house of the 1930s, IAPI (Retirement and Pension Industry Institute), the second from the 1990s CDHU (Urban Housing Development Center) and the third from 2015 MCMV (My House My Life). The result indicates that the materials used in the dwellings of the IAPI program and of My House My Life complies with the minimum to the construction guidelines standards and the CDHU program does not reach the specifications of the ABNT. It is concluded that to produce a home with thermal comfort of social interest it's necessary that the choice of materials guarantee the thermal performance that complies with the bioclimatic zoning of each region of Brazil and the needs of the user. abstract should be a maximum of 200 words. The text on the abstract should not have paragraphs.

**Keywords:** Housing, thermal comfort and ABNT 15229-3 standards.

### Introduction

Homes of social interest in Brazil, exerts a fundamental role in the lives of citizens, with a reference to protection, ownership, family and to belong to a society that expresses culture, beliefs and yearnings inside a urban life, BONDUKI (1998).

According to City Ministry (2016), the goal is the reduction of a housing deficit for the population that have a salary of 0-5 minimum wages. The housing issue was restricted to a numerical problem, ignoring social, cultural and climatic aspects. The unit destined to this population does not contemplate the aspects that guarantee the thermal comfort, flexibility and special accessibility, reforming or enlargement that meets with security.

Today, housing construction prioritizes low cost, not allowing thermal comfort in rooms, and does not favor family living, which plays a key role in promoting human development and quality of life.

Ferreira (2012) says, "Good architecture has an emancipatory character and a fundamental role in promoting quality of life and human development. Houses that do not allow family living, which do not offer spaces for family reunion, an area for playing and studying for children, do not create conditions for personal, family and collective development."

The construction of homes of social interest in Brazil in the twentieth century, does not address the issue of thermal comfort in buildings in relation to the local climate, but in the XXI century the projects are elaborated according to the climatic conditions and indications of the construction standards of NBR 15220. The development of homes of social interest in the country, due to the centralization of decisions, the projects were standardized and applied indiscriminately throughout the national territory, that is, models and constructive systems were adopted as a national model of housing.

Halfway through the last century, several researchers studied the climatic conditions and the interaction of man and his development in the physiological and comfort responses in the built environment.

The Olgay brothers (1963), in the 60s, developed a diagram, the Olgay bioclimatic chart, with data of dry bulb temperature and relative air humidity in the period of one year. The result defined strategies for each comfort zone in different regions of hot and humid climates and temperate regions.

Givoni (1992) extended the method of the Olgay brothers, he considered the building with an internal climate different from the external one, extending the zone of comfort and related to the changes of the external climatic conditions and its surrounding. The bioclimatic chart of Givoni is suitable for Brazil, a country with a hot climate.

The norm NBR 15220-3 (ABNT, 2005), divides Brazil into 8 bioclimatic zones that have specific comfort strategies for each zone attending the summer and winter periods. The specimens studied have indications in the projects of materials and constructive systems in the housing programs. The buildings built in the 1930s and 1990s are still inhabited today, so check the thermal performance and compare the architectural designs with the current housing project, check whether it meets the different climatic realities of the country and the comfort of the residents.

## Goal

The objective of this work is to analyze and compare three housing units of social interest, one-story houses, related to the surrounding materials, the thermal comfort variables that meet the ABNT 15220 standards with specifications and constructive guidelines, bioclimatic strategies for the entire Brazilian territory.

## Method

In order to choose the object of study, in the bibliographic survey, it was identified three important moments in the trajectory of the development of homes of social interest in Brazil that were: the first housing unit of the 1930s, IAPI (Retirement and Pension of Industry Institute) projects with the modernist concept of laminate-shaped buildings and individual houses without ornaments and minimal design, the second from the 1990s CDHU (Urban Housing Development Center) projects with minimal design, but with a expansion project, and some buildings have constructive

innovation such as metal structure and an enclosure of a cement board, and the third from 2015 MCMV (My house My life) a simple and low cost project.

The examples of dwellings presented in this work are projects of approved ground houses, executed and handed over to the population.

The total built area of the IAPI house is 39.15m<sup>2</sup>, in the city of Santo André; CDHU 37.97m<sup>2</sup>, in the city of São Carlos and MCMV 32,35m<sup>2</sup> in the city of Manaus, all specimens have a close design example below (Figure 1).



Figure 1. 1a. IAPI (1930); 2a. CDHU (1990); 3a. MCMV (2015)

The characteristics of the enclosure, wall and roof materials, between the specimens are different due to the evolution of the materials used in the constructions of each period (Table 1).

Table 1. Design and Physical Characteristics of the Materials

PROJECT	CLOSING		PHYSICAL CHARACTERISTICS
IAPI	Wall	Solid Brick masonry (10,0x6,0x22,0 cm), mortar of 2,5 cm internal and external totaling 15cm of thickness	
	Roof	Flat Clay tile(1 cm) with wooden lining with thickness of 1 cm	
	Openings	Wooden frames (Cedro and Peroba Rosa)	
	Floor	Floor with wooden Friezes	
CDHU	Wall	Concrete block masonry (9,0x19x39,0 cm), 2cm external and internal coating mortar	
	Roof	Clay tile of 1 cm unlined	
	Openings	Steel frames	
	Floor	Ceramic floor	

MY HOME, MY LIFE				
			Wall	Ceramic brickwork of 6 holes (10, 0x15, 0x20 .0 cm) mortar 0.5 cm coating internal and external
			Roof	Fiber cement tiles of 0,5 cm with PVC or wood lining in every rooms
			Openings	Wooden frames of law or metallic
			Floor	Cemented Floor

The NBR 15220 - Thermal Performance of Buildings Part 3: Brazilian bioclimatic zoning and constructive guidelines for single-family homes of social interest, brings the recommendations for the summer and winter periods, the percentage of opening area, physical properties of materials for walls and rooves (Table 2).

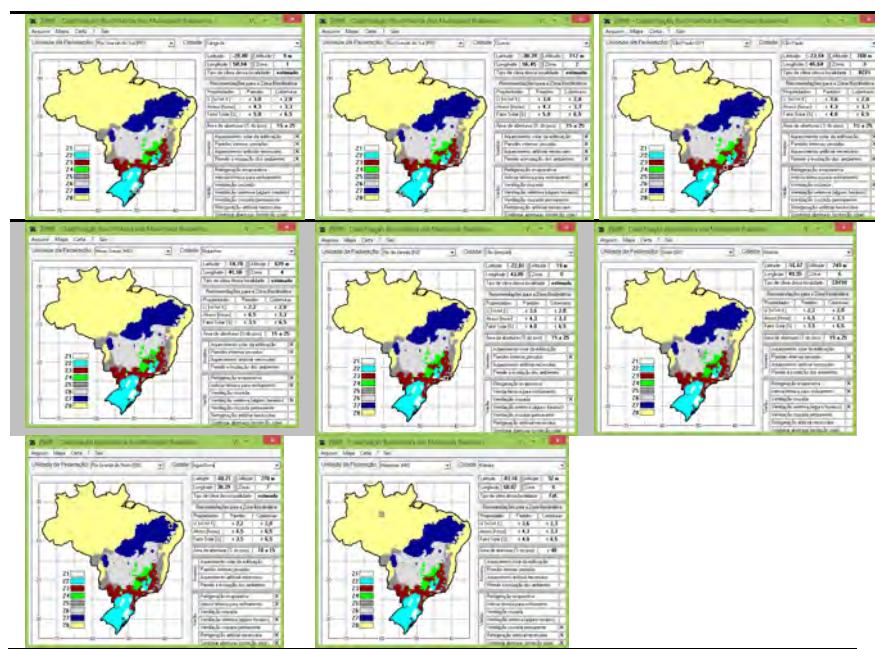
Table 2. Recommendations for constructive guidelines and strategies for passive thermal conditioning.

ABNT 15220-3	OPENING	SHADING	EXTERNAL CLOURE	STRATEGIES
<b>ZONE 1</b>	Average 15%<A< 25%	Allow sunshine during the cold period	Lightweight wall, light and insulated cover	Summer: J) cross ventilation; Winter: B) Solar heating of the building; C) Heavy internal seals (inertia). Insufficient passive in cold period
<b>ZONE 2</b>	Average 15%<A< 25%	Allow sun during winter	Lightweight wall, light and insulated cover	Winter: B) solar heating of the building; C) Heavy internal seals (inertia). Insufficient Passive in winter
<b>ZONE 3</b>	Average 15%<A< 25%	Allow sun during winter	Light reflective wall, light and insulated cover	Summer: J) cross ventilation; Winter: B) Solar heating of the building; C) Heavy internal seals (inertia).
<b>ZONE 4</b>	Average 15%<A< 25%	Shade openings	Heavy wall, light and insulated cover	Summer: H) Evaporative cooling and thermal mass for cooling; J) selective ventilation; Winter: B) Solar heating of the building; C) Heavy internal seals (inertia).
<b>ZONE 5</b>	Average 15%<A< 25%	Shade openings	Light reflective wall, light and insulated cover	Summer: J) selective ventilation; Winter: C) Heavy internal seals (inertia).
<b>ZONE 6</b>	Average 15%<A< 25%	Shade openings	Heavy wall, light and insulated cover	Summer: H) Evaporative cooling and thermal mass for cooling; J) selective ventilation; Winter: C) Heavy internal seals (inertia).
<b>ZONE 7</b>	Small 10%<A< 15%	Shade openings	Heavy wall, heavy cover	Summer: H) Evaporative cooling and thermal mass for cooling J) selective ventilation
<b>ZONE 8</b>	Large: A>40%	Shade openings	Light reflective wall, reflective light coverage	Summer: J) permanent cross ventilation; Insufficient passive in the hottest hours.

The identification of the bioclimatic zone for each home of social interest found in different cities of Brazil used the software ZBBR, Brazilian Bioclimatic Zoning. The software gives the recommendations for each bioclimatic zone according to the NBR 15220-3 standards.

In this paper, eight Brazilian cities were selected, one for each bioclimatic zone. The choice of cities was due to the availability of climatic archives in the ZBBR program, to guarantee the verification of the thermal performance of buildings in a greater number of different climates, distributed throughout the national territory. The cities are: Xangri-lá, RGS (Zone 1), Quaraí, RGS (Zone 2), São Paulo, SP (Zone 3), Biquinhas, MG (Zone 4), São Gonçalo, RJ (Zone 5), Goiâna, GO (Zone 6), Água Nova, RN (Zone 7), Manaus, AM (Zone 8) (Table 3).

Table 3. Results of the ZBBR software for each Bioclimatic Zone of Brazil.



For each bioclimatic zone, it follows recommendations of transmittance, thermal delay and solar factor for wall, roof and percentage for openings (window) in relation to the floor of the environment.

With the data obtained in the software for each bioclimatic zone of Brazil, it is possible to verify if the building is meeting the constructive specifications for the best thermal performance of the building. With the knowledge of the materials used in the walls, roofing and sizing of the window areas for each environment, a comparative analysis was carried out with each typology with the different climatic zones. The comparative analysis between the examples of homes of social interest and climatic variations began with the period and construction system, type of material for sealing: walls and roofs and areas of openings (windows). The thermal transmittance ( $U$ ), the thermal coefficient ( $C_t$ ), the thermal delay ( $\phi$ ) and the opening area in relation to the floor area of the environment of each type of dwelling were calculated. It is important to choose the building material for each type of bioclimatic zone that generates different thermal behavior in which it can lead or create resistance to heat, providing comfort inside the building.

## Results

Table 3 shows the results of the social housing projects IAPI, CDHU and MCMV with the types of sealing (wall, roof and opening), with the data of thermal transmittance (U), the thermal coefficient (Ct), the thermal delay ( $\omega$ ) and the opening area compared to the constructive recommendations of the NBR 15220-3, 2005.

The result indicates that the materials used in the IAPI and MCMV are minimally compliant with the standards' constructive guidelines and the CDHU program does not meet all the specifications of the standards set (Table 3).

Table 3. Results of the homes of social interest and of the recommendations standards.

PROJECT	FENCE	MIN 15% MAX 40%	THERMAL TRANSMITTANCE (U)	THERMAL CAPACITY (Ct)	THERMAL DELAY ( $\Phi$ )	MEETS							
						Xangri- lá (RS) Z1	Quaraí (RS) Z2	São Paulo (SP) Z3	Biquinhas (MG) Z4	São Gonçalo (RJ) Z5	Goiânia (GO) Z6	Águas Nova (RN) Z7	Manaus (AM) Z8
IAPI	Wall	–	3,13	255	3,8	NO	NO	NO	NO	YES	NO	NO	YES
	Roof	–	2,00	32	1,3	YES	YES	YES	YES	YES	YES	NO	YES
	Opening	15%	–	–	–	YES	YES	YES	YES	YES	YES	YES	NO
CDHU	Wall	–	2,78	209	4,5	NO	NO	NO	NO	NO	NO	NO	NO
	Roof	–	4,55	18	0,3	NO	NO	NO	NO	NO	NO	NO	NO
	Opening	15%	–	–	–	YES	YES	YES	YES	YES	YES	YES	NO
MY HOME MY LIFE	Wall	–	2,48	159	3,3	YES	YES	YES	NO	YES	NO	NO	YES
	Roof	–	1,76	24	1,2	YES	YES	YES	YES	YES	YES	NO	YES
	Opening	15%	–	–	–	YES	YES	YES	YES	YES	YES	YES	NO

With the comparative analysis, the recommendations and constructive guidelines for each bioclimatic zone, the indications for social housing, IAPI, CDHU and MCMV and to achieve thermal comfort within the rooms, the following design parameters are indicated:

Zone 1: IAPI (wall); CDHU (wall and roof)

Wall sealing (Winter: heavy inner walls, artificial heating required);

Roof sealing (Winter: solar heating of the building);

Zone 2: IAPI (wall); CDHU (wall and roof)

Wall sealing (Winter: heavy inner walls, artificial heating required);

Roof sealing (Winter: solar heating of the building);

Zone 3: CDHU (wall and roof)

Wall sealing (Winter: heavy inner walls)

Roof sealing (Winter: solar heating of the building);

Zone 4: IAPI (wall); CDHU (wall and roof); MCMV (wall)

Wall sealing (Winter: heavy inner walls), (summer: thermal inertia for cooling)

Roof sealing (Winter: solar heating of the building), (summer: evaporative cooling)

Zone 5: CDHU (wall and roof)

Wall sealing (Winter: heavy inner walls), (summer: reflective walls)

Roof sealing (Winter: solar heating of the building), (summer: light and isolated)

Zone 6: IAPI (wall); CDHU (wall and roof); MCMV (wall)

Wall sealing (summer: thermal inertia for cooling)

Roof sealing (summer: evaporative cooling)

Zone 7: IAPI, CDHU and MCMV (wall and roof)

Wall sealing (summer: thermal inertia for cooling)

Roof sealing (summer: evaporative cooling)  
Zone 8: IAPI (wall); CDHU (wall, roof, opening); MCMV (opening)  
Wall sealing (light and reflective)  
Roof sealing (light and reflective)  
Opening [permanent cross ventilation, shade openings (sun protection)]

Housing projects of social interest in three distinct periods in Brazil indicate project modifications, change of materials for wall and roof enclosures, rational design of the openings and the result to obtain the internal comfort of the dwellings for the majority of the bioclimatic zones, reached in a minimum way the recommendations and constructive guidelines of the standards set, resulting in an adequate project, economically feasible, but that does not guarantee the thermal comfort to the user and the best internal use of the building.

## Conclusion

It is concluded that to carry out the construction of a home of social interest with thermal comfort it's necessary to understand the climate of each region, adopting the recommendations and guidelines of the ABNT 15220-3 standards that allows small changes in the projects in homes of social interest already existing, that meets a significant reduction in thermal discomfort within a building. The choice of construction material suitable for each type of zoning, construction system and opening area are solutions that can improve the level of comfort in the summer to meet the needs of the user, reconciling goals, culture and family life.

## References

- ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 15220: Desempenho térmico de edificações – Parte 3: zoneamento bioclimático brasileiro e diretrizes construtivas para habitações unifamiliares de interesse social. Rio Janeiro, 2005.
- BONDUKI, Nabil. **Origens da habitação social no Brasil** - Arquitetura moderna, Lei do Inquilinato e difusão da Casa Proletária. São Paulo: Estação Liberdade, 1998.
- FERREIRA, J. S.W. **Producir casas ou construir cidades? Desafios para um novo Brasil urbano.** 1<sup>a</sup> Edição FUPAM, São Paulo, SP, 2012.
- GIVONI. **Confort climate analysis and building design guidelines.** Rev. Energy and Building 18 (1) Lausanne, 1992.
- Ministério das Cidades. [www.cidados.gov.br](http://www.cidados.gov.br) (acesso 21.11.2016)
- OLGYAY, V.; OLYGAY, A. **Design with climate.** Princeton: Princeton University Press, 19



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Thermal comfort in the Holy Rosary Church, Bangkok

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**Abstract:** The Holy Rosary Church, one of the oldest historic churches in Thailand, still serves various Roman Catholic ceremonies throughout its 120-year history. Although Thailand has a long period of high temperature, the church employs natural ventilation combined with mechanical fans during Mass and religious activities. Five data loggers have been employed at different points in the building to measure temperature and relative humidity for a year. Finally, data collection is plotted into bioclimatic charts to indicate thermal comfort condition in different seasons as well as adaptive method employing average outdoor temperatures was simulated. The occupants' comfort and satisfactions are also evaluated. The questionnaire results show that in every season the users feel moderately comfortable during the Mass within the ranges of temperature, RH and wind speed of 26-33°C, 40-84% and 0.3-1.1 m/s respectively. The research outcome indicates that an efficient ventilation system can optimize occupants' thermal comfort.

**Keywords:** Thermal comfort, Catholic Church, comfort scale, bioclimatic chart, adaptive model

### Introduction

The Holy Rosary Church represents the resettlement of the Portuguese Catholics in Bangkok, after the collapse of Ayutthaya realm and its age will be 120 years old in this September, 2017. This Gothic Revival Style church was built in ca. 1890 (2433 B.E.), consecrated in 1897 (2440 B.E.). This historic building won an Architectural Conservation Award from the Association of Siamese Architects in 1987. It is located in Samphanthawong District, on the eastern bank of Chao Phraya River and has been accommodating community activities for ages.

However, the impact of climate change and changing of land use around the church have significantly affect the thermal comfort perception of the occupants, as an increase in external temperature influences directly on the internal climate of building. (Nemachoua, et al., 2017). The church provides several ceremonies for the Catholics, including Mass, praying the rosary, funeral Mass, and wedding ceremony, etc. and when the church is occasionally overcrowded, natural ventilation through existing operable windows might not be enough to make occupants feel comfortable, especially in summer period. Moreover, most of the historic churches in Bangkok have installed large air-conditioning systems, as some parishioners thought to be the proper solution to improve indoor thermal environment. Only A few churches still employing natural ventilation strategy or using simple mechanical fans with supplementary evaporative coolers (mini-split systems). However, the physical conditions of the church and its historical importance have to be carefully considered, our research team are aiming for the optimum solution both for improving environmental comfort and building conservation.

The objectives of this research are to investigate the thermal performance of the building and thermal comfort satisfaction of the occupants. The results of the studies will suggest how to improve thermal comfort conditions for the Holy Rosary Church to enhance its historical values. This study is composed of six parts namely 1) Literature reviews 2) Building surveys 3) Thermal performance measurement 4) Field surveys 5) Results and 6) Discussion and Design solution.

## Literature Review

### ***Architectural characteristics and importance of the Holy Rosary Church***

According to the previous study (Suriyothin, 2016) 'Interior Lighting Design for the Holy Rosary Church, Bangkok, an important characteristic of the Holy Rosary church lies in its employment of the Gothic Revival style. The building utilizes a load-bearing wall structure with a timber framed roof truss system. Decorated with stencil painting, the interior curved ceiling is of wooden boards placed longitudinally along the length of the main roof. One of the key decorative features of the building is its beautiful stained glass windows which allow natural light to shine through. However, there are small openable areas underneath the window units allowing cross ventilation through the interior space.

### ***Thermal comfort***

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation of six factors namely, metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. It is possible for all six of these factors to vary with time. (55-2013, 2013). As the air temperature increases, convection cooling is reduced. As air temperature exceeds skin temperature, the body begins to gain heat from the environment. The rate of convective heat loss is also affected by the speed of the air movement across the skin's surface (Moore, 1993). Air movement accelerates convection, but also changes the skin and clothing surface heat transfer coefficient, as well as increases evaporation from the skin, thus producing a psychological cooling effect. Li et al. (2014) states that thermal comfort and human health demands need sufficient amount of fresh outdoor air. In a natural ventilated building, occupants may endure higher temperature as a study shows significantly wider range of temperatures are accepted by the occupants, which fall out of the Fanger's thermal comfort standard (ISO 7730, 2005). High humidity restricts evaporation from skin and in respiration, and thus kerb the dissipation mechanism (Szokolay, 2004). As skin temperature increases, perspiration increases, and the skin is cooled by evaporation. The rate of evaporation is dependent on both the relative humidity and velocity of surrounding air (Moore, 1993). Radiation exchange depends on mean radiant temperature. Clothing is the thermal insulation of the body. If clothing can be freely chosen, it is an important adjustment mechanism, but if it is constrained in a warm environment, it should be compensated for by a cooler air temperature. Acclimatisation and habit is a strong influence, both physiologically and psychologically (Szokolay, 2004). Gender, age, and climate conditions all have an impact on the thermal comfort perceived by the occupant (Nicol & Humphreys, 2002) (Smolander, 2002). Location and typology of the building along with outdoor climate and season also influence thermal comfort of occupants (Frontczak & Wargocki, 2011).

### ***General Climatic Conditions of Bangkok, Thailand***

The weather in Bangkok is dominated by a tropical monsoon climate. It can be divided into three seasons, hot, rainy and winter (cool), although temperatures are fairly hot year-round, ranging from an average low of 22.0 °C (71.6 °F) in December to an average high of 35.4 °C (95.7 °F) in April. The rainy season begins with the arrival of the southwest monsoon around mid-May. September is the雨iest month. The rainy season lasts until October, when the dry and cool northeast monsoon takes over until February. The hot season is generally dry, but also sees occasional summer storms (Climatic Group, 2012). Furthermore, in winter, sometimes it is really hot and once the rain comes; the temperature could suddenly drop 5-7 °C (Sreshthaputra, 2014).

### ***Adaptive Comfort Standard (ASHRAE 55-2013)***

As a design standard for naturally conditioned spaces, one might first use a building simulation tool to predict what indoor conditions might be achieved. The Adaptive Comfort Standard could then be used to determine whether those thermal conditions are likely to be acceptable. If they are not acceptable, then design modifications might be made (i.e., to the thermal mass or fenestration), and the process repeated. If such changes prove to be ineffectual in subsequent simulations, a decision to air condition might then be appropriate. Adaptive Model is a model that relates indoor design temperatures or acceptable temperature range to outdoor meteorological or climatological parameters (55-2013, 2013).

### ***Thermal Comfort and Adaptive Comfort Studies***

Chitkhachonwanit (2004), Rasitanon (2010), Rasrisut and Nuntasiri (2015), each presented a new chart of comfort zone for local people and adaptability to living in Thailand in different regions or communities. The results show that people were able to adjust themselves to meet their preferred thermal environments thus, their perceptions and expectations of thermal comfort differ from ASHRAE standard. Asavavichai, et al. (2015) found that Thai elderly had different thermal comfort preferences from average Thai adults. They preferred a little warmer temperature, more humid air and more wind speed than normal. Higher temperature settings would allow significant cooling energy savings, as Toftum, et al. (2000) indicates that 28°C is overwhelmingly preferable to 26°C if the subjects in the warmer environment are permitted to select their own preferred airspeed. de Dear and Brager (2002) summarised that outdoor climate influences thermal perceptions beyond just the clothing that we wear. It probably has a psychological effect on expectations, particularly in naturally ventilated buildings that are more closely connected to the natural swings of the outdoor climate. Thus, the Adaptive Comfort Standard (ACS) was developed using mean monthly outdoor temperature as the input.

### ***Methodology***

In order to investigate the thermal comfort performance in the church, the methodology are divided into three steps namely building surveys, thermal performance measurement and field surveys.

#### ***Building surveys***

First of all, the researcher observed the functions of the church; architectural condition, ventilation systems, human behaviors, and schedules in different ceremonies along the observation period between April, 2016 and May, 2017

### ***Thermal performance measurement***

The thermal comfort measurements have been observed from June, 2016 - May, 2017. Temperature, RH, and wind velocity are measured by HOBO U12 data logger, Testo 350-XL, Testo 454 and Tenmars TM-4001 Hot Wire Anemometer, respectively.

HOBO data loggers were installed on five positions inside the building as shown in Figure 1. The collected data were plotted into the Bioclimatic charts to be analysed. Wind velocity data was collected in the beginning of winter, mid-winter, and the beginning of summer with 18 positions inside the church on Sunday after the Mass finished around 9:00, 11:00 and 20:30.

### ***Field surveys***

To analyse thermal comfort, questionnaires were given to the parishioners during the Mass in observation period. The questionnaire comprises personal information, occupants' environment importance, thermal comfort preference and expectation.

Indoor air temperature data from HOBOs, prevailing mean outdoor temperature from the Department of Drainage and Sewerage and air speed were input to the CBE thermal comfort tool (2013) to find out whether the condition in each case complies with ASHRAE Standard 55-2013.

## **Results**

### ***Building survey***

The church was built in 1891 and its wall bearing is the main structure. The roof was created by wooden truss with terra cotta tiles. The plan is symmetry and the orientation of this building is East-West. The river seems to give benefits to the church since the West side of it can percept the cool air. However, the entrance of the church faces the large concrete surface on the West side leading heat and light reflecting into the building through the opened-doors. As seen in Figure 1, the church is divided into three zones namely the entrance: porch, the middle area: nave-sanctuary and sacristy.

The existing ceiling and wall mounted mechanical fans in the church are allowed to be freely operated by parishioners during the Mass and other ceremonies both for the nave and the sanctuary. Additionally, in the evening Mass which always full of parishioners, the evaporative cooling fans are employed for the priests who wear the high clo-values clothing.

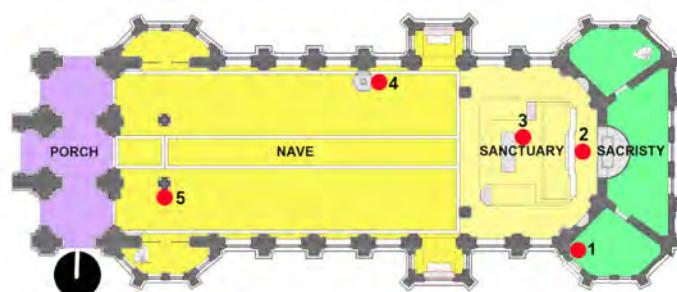


Figure 1 Floor plan of the holy rosary church with HOBO positions and zoning

### ***Thermal performance measurements***

There are three data sets rely on the seasons in Thailand: rainy season (June-October, 2016), winter (October, 2016-March, 2017) and summer (March-May, 2017) (Meteorological Department, 2017). The data were plotted in different forms of graph and the researcher

decided to analyse the data ranges from 19:30 to 20:30 on at the nave since it contained the highest numbers of occupants compared with the other periods.

The results show that during the rainy season, a fluctuation in outdoor and indoor temperature and RH was found. As shown in Figure 2, the outdoor temperature decreased to 24-26°C several times due to the rain while the indoor temperature remained higher. In winter and summer, the indoor temperatures varied in relation to the outdoor temperatures, also the ranges of RH were lower as they are both dry seasons. However, in summer the indoor air temperature was higher and the RH was lower than the outdoor.

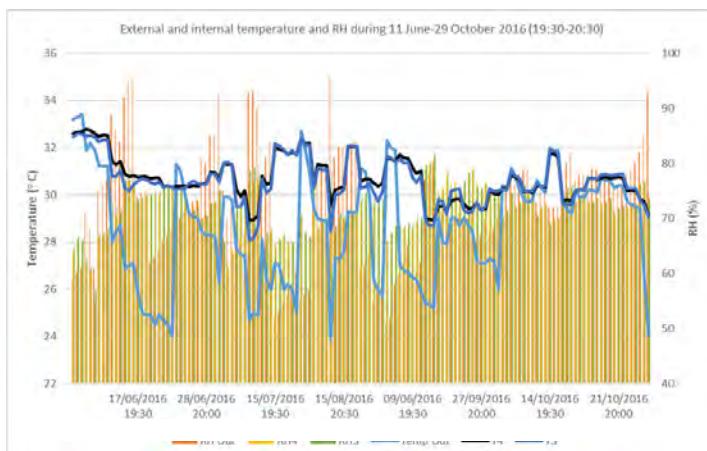


Figure 2 External, internal temperatures and RH in rainy season around 19:30-20:30 on Sunday

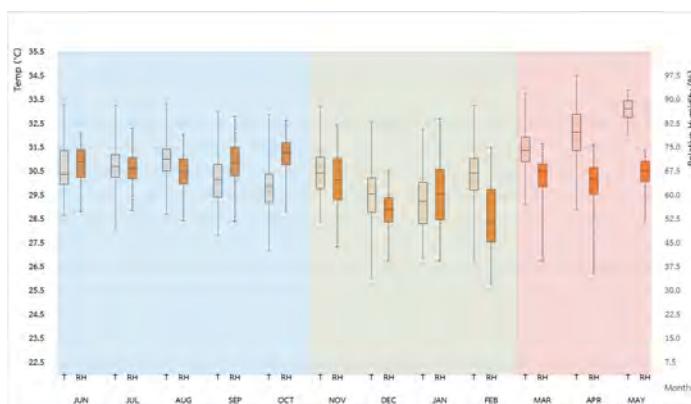


Figure 3 Internal air temperatures and RH in the nave from June, 2016- May 2017

Figure 3 shows the internal air temperature and RH at one of the measuring point in the nave. In winter, the temperature and RH ranges were broader than in rainy season. However, in summer, the maximum temperature was highest throughout the data collecting period and the minimum RH was a little less than in winter.

### **Field surveys**

According to the questionnaires, there are 337 responses along the observation period. The ages of the participants ranges from 16 to older than 60 years old. The overwhelming majority of them fell into 46-60- year-old group which is 28%, followed by a 13-30-year-old group and older than 60 year-old group, which accounted for 27% and 25% respectively. 63% of the responses are weekly attendants. Overall, the numbers of female are as twice as male. Around 93% are parishioners. Most participants (35%) wore T-shirt or short-sleeve, trousers and sandals (0.53 clo) with the second largest (10%) wore T-shirt, shorts and

sandals (0.22-0.24 clo). The priests, who usually stand at high altar, always wear underwear (thin T-shirt), long trousers, long-sleeve (robe) and vestment (1.24 clo).

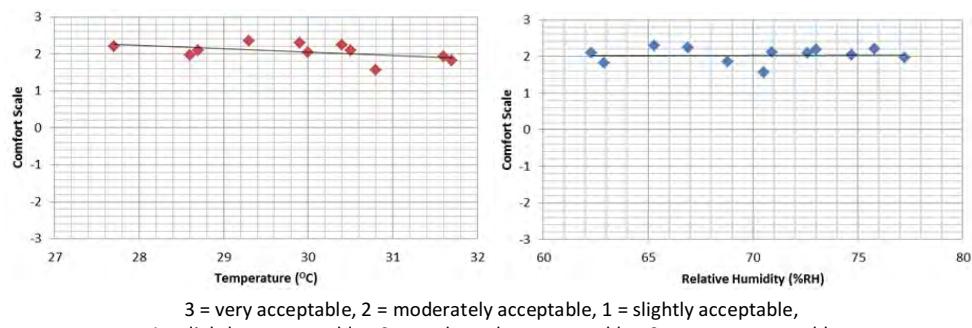


Figure 4 The comfort scale of indoor temperature and humidity

The comfort scale (Figure 4) show that most participants felt moderately acceptable to thermal environment during the Mass in most seasons. However, the higher the temperature the comfort line tends to decrease while the relative humidity do not make any different in comfort.

The last charts (Figure 5) present the adaptive models that rely on the entire data collected during rainy season from the field surveys, and the bioclimatic charts were also plotted during the evening Mass.

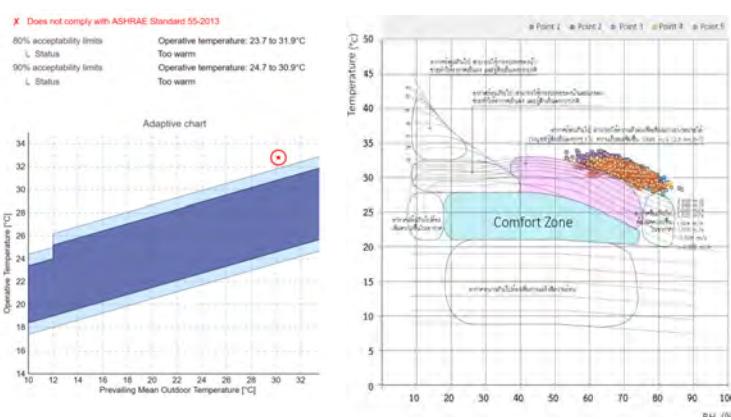


Figure 5 (left) Adaptive model in rainy season with operative temperature 32.8°C, prevailing mean outdoor temperature 30.2°C and air speed 0.6m/s (Tyler, et al., 2013) (right) Bioclimatic chart during rainy season between 19:30-20:30

## Discussion and Design Solution

**Users:** As mentioned earlier, the majority of the occupants were females and they were older than 46 years old, which both groups prefer warmer temperatures than average. Almost half of the attendants dressed with the clothing value range of 0.22-0.53. Some occupants claimed that they were only focusing on the ceremony, which such activity requires low metabolism rate and short period of time. As a result, the effect of thermal environment becomes less important to them. It is also noticeable that occupants prefer to sit close to the mechanical fans which are freely operable according to their own needs.

**Thermal Environment:** The results show that occupants feel moderately comfortable during the Mass, within the temperature range of 26-33°C and 40-84% RH while the wind speed range is 0.3-1.1 m/s. The bioclimatic charts of summer and rainy seasons illustrate uncomfortable indoor environment which contradicts the questionnaires results. However,

it is found that in every month, the maximum indoor temperature is higher than the mean outdoor temperature around 1-3.5 °C. The less the temperature difference, the more wind speed complies with ASHRAE standard 55-2013. Hence, increasing air speed and providing uniformly distribution could be an appropriate technique to improve thermal comfort.

**Design Solution:** As occupants also express concerns on building conservation, a strategy of utilising free standing mechanical fans were tested. The fans were installed in front of the operable windows to increase the induction of natural wind flow. As a result, this seems to be an optimum design solution to improve thermal comfort as it can actually increase indoor wind velocity (comparing to the existing wall-mounted mechanical fans) and also minimise visual and physical impact on existing building condition. Meanwhile, occupants have also been adapting their lifestyle according to their preferred thermal conditions, such as, wearing clothing with lower clo value, changing seating location, etc. As a result, occupants are satisfied with the improved thermal condition. However, other mechanical systems may be considered if the indoor air temperature is much higher than the mean outdoor temperature which thermal comfort may not be improved by increasing air speed.

### **Conclusion and Further Study**

Thermal comfort improvement in historic building is rather difficult due to its physical constraint. However, the simplest way is to provide appropriate environmental strategy along with the ability to control over indoor thermal environments for occupants, such as freely operable openings and mechanical fans, etc. as they can also adapt their behaviours to restore their comfort. Besides, the church will be restored after the 120<sup>th</sup> Anniversary. Hopefully, this research will be one of the design alternatives as well as a starting point for the use of an appropriate technology for a sustainable building refurbishment projects in the future. It is suggested to further study on this specific type of building, as culture and religious belief might affect psychologically on occupants.

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### **References**

- 55-2013, A.-A. S. (2013). *Thermal Environmental Conditions for Human Occupancy*. [Online] Available at: <http://www.ansi.org> [Accessed 20 March 2017].
- Asavavichai, K., Netipongpiroj, A. & Sreshthaputra, A. (2015). *Thermal Comfort Preference of Elderly in Thailand*. s.l., The 55th Kasetsart University Annual Conference.
- Chitkhachonwanit, K. (2004). *Thermal Comfort and Adaptibility to Living for Local People*, s.l.: Institute of Research and Development, Silpakorn University.
- Climatic Group, M. D. B. (2012). *The Climate of Thailand*. [Online] Available at: [https://www.tmd.go.th/en/archive/thailand\\_climate.pdf](https://www.tmd.go.th/en/archive/thailand_climate.pdf) [Accessed 3 March 2017].
- DDS, 2017. Department of Drainage and Sewerage. [Online] Available at: <http://dds.bangkok.go.th/services.php> [Accessed 20 May 2017].
- de Dear, R. & Brager, G. S. (2002). Thermal comfort in Naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings*, Volume 34, pp. 549-561.
- Frontczak, M. & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Build Environ*, 46(4), pp. 922-937.

ISO 7730, (2005). *Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, s.l.: International Standards Organisation (ISO).

Li, H., Li, X. & Qi, M. (2014). Field testing of natural ventilation in college student dormitories (Beijing, China). *Building and Environment*, Volume 78, pp. 36-43.

Meteorological Department, 2016. <https://www.tmd.go.th/en/index.php>. [Online] Available at: <https://www.tmd.go.th/en/index.php> [Accessed 20 June 2016].

Moore, F. (1993). *Environmental Control Systems: Heating Cooling Lighting*. Singapore: McGraw-Hill, Inc..

Nemachoua, K. M., Ricciardi, P., Reiter, S. & Yvon, A. (2017). A comparative study on optimum insulation thickness of walls and energy savings in equatorial and tropical climate. *International Journal of Sustainable Built Environment*.

Nicol, J. F. & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable standards for buildings. *Energy Build*, 34(6), pp. 563-572.

Rasisuttha, S. & Nuntasiri, P. (2015). Thermal Comfort of Low Income People: Case Study od Baan Mankong Non Nong Wat 2. *Academic Journal: Faculty of Architecture, Khon Kaen University*, 14(2), pp. 127-141.

Rasitanon, T. (2010). *Thermal Comfort and Adaptability to Living for Muslim on the Coast Area Songkla Province*. Bangkok: Architecture Thesis, Silpakorn University.

Smolander, J. (2002). *Effect of cold exposure o older humans*. [Online] Available at: <http://dx.doi.org/10.1055/s-2002-20137> [Accessed 20 Mar 2017].

Sreshthaputra, A. (2014). *Living Green*. Bangkok: Amarin Printing & Publishing.

Suriyothin, P. (2016). Interior Lighting Design for the Holy Rosary Church, Bangkok. *Nakhara*, Volume 12, pp. 149-164.

Szokolay, S. V. (2004). *Introduction to Architecture Science: the basis of sustainable design*. Oxford: Elsevier.

Toftum, J. et al. (2000). *Human Response to air Movement. Part I. Preference and Draft Discomfort*, Lyngby: DTU Internayional Center for Indoor Environment and Energy.

Tyler, H. et al. (2013). CBE Thermal Comfort Tool. [Online] Available at: <http://cbe.berkeley.edu/comforttool/> [Accessed 2 April 2017].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Effect of Plan Layout on Electricity Consumption to maintain Thermal Comfort in Apartments of Dhaka**

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**Abstract:** This paper reports on a study of electricity consumption, for achieving thermal comfort, in apartments of tropical Dhaka, the capital of Bangladesh, which is one of the most densely populated cities in the world. As approximately 45% of the total population of Dhaka constitutes the middle income and upper-middle income groups, electricity consumption by this group is a critical factor in the national energy balance. According to recent reports, the electricity consumption in the residential sector has almost doubled in six years. While domestic electricity consumption is considered in three sectors, for lighting, for cooling and for household appliances, this discussion focuses only on that consumed for cooling. During the warm months (March-October), ventilation and air movement is vital for thermal comfort in the tropics, and electrical cooling appliances are commonly used for the purpose. The target middle income group resides in apartments of floor area between 93-149m<sup>2</sup> (1000-1600sft). A field survey was conducted, whereby scaled drawings of plan layout of the apartments were obtained, to understand the spatial quality of the existing apartments. Two basic types of layouts were found mostly used in Dhaka; defined in the study as “open type” and “cellular type” layouts. A questionnaire survey was conducted on sample units, to determine the specifications of electrical appliances being used for cooling and to assess the comfort situation of the inhabitants. It was the contention of this study that there could be a critical analysis of plan layouts in mid-rise apartment buildings, to determine whether there is a relationship between the energy consumption and the layout of these plans. Analysis of the findings from the survey and the questionnaire responses reveal that, plan layout does, indeed, have a significant impact on electricity consumption needed for thermal comfort.

**Keywords:** Electricity Consumption, Thermal Comfort, Cooling Loads, Plan layout, Domestic Architecture

### **Introduction**

Dhaka, the capital of Bangladesh, is one of the most densely populated cities in the world. As approximately 45% of the total population of Dhaka constitutes the middle income and upper-middle income groups (Islam, 2004), electricity consumption by this group is a critical factor in the national energy balance. According to reports, the electricity consumption in the residential sector has almost doubled in years from 2006 to 2012 (DESCO, 2012). With the rising demand for electricity in the residential sector, it is necessary to adopt passive design features while designing residential buildings for middle income group in planned residential areas of Dhaka city. While domestic electricity consumption is considered in three sectors, for lighting, for cooling and for household appliances, this discussion focuses only on that consumed for cooling. Reporting on a recent study (Tariq, 2016), the paper discusses whether electricity consumption can be related to plan layout, in terms of, spatial quality, in apartment units inhabited by middle income group, in Dhaka.

## **Research Methodology**

A Literature survey was conducted to gain a theoretical understanding of factors affecting indoor thermal comfort, electricity consumption for cooling, elements of built form that affect electricity consumption, on passive design strategies, and on the evolution of the apartment in the housing sector in Bangladesh along with different layouts which are mostly inhabited by middle and upper-middle income group of Dhaka city.

This was followed by a survey on south oriented apartments of floor area between 93-148.7m<sup>2</sup> (1000-1600sft), representative of target middle and upper-middle income group, located in planned residential areas of Dhaka city, selected on a random sampling method. As planned residential areas have fixed sizes of plots, the buildings in these areas show some common characteristics in terms of plan layout typology, building envelope, building height and volume. The final sample size was determined from 20% of an initial survey, consisting of variable plan layouts, but with similarities in other building features. A limited questionnaire survey was simultaneously undertaken to determine the nature and specifications of electrical appliances used for cooling, and to record the comfort perception of the inhabitants. Scaled drawings of plan layout were also collected to understand the spatial quality of the apartments, in an attempt to categorise the layouts and compare with the measured data/variables and responses. Other passive features, which are known to be associated with thermal comfort in a built-environment, like orientation, wall thickness, opening sizes, shading details and surrounding building configurations were consciously kept similar among the finally selected study apartments.

Analysis of the findings from the survey was conducted to determine whether different types of plan layout in South oriented apartment units, have any significant impact on electricity consumption needed for thermal comfort as these units are exposed to maximum duration of solar exposure. Finally, suggestions for energy efficiency were attempted from the analysis.

## **The Investigation**

An open type questionnaire was prepared, based on the theoretical understanding of issues related to energy consumption in residential buildings, and several energy consumption assessment questionnaires, particularly from the "Smart Living Handbook". A pilot survey was then conducted on a randomly selected residential apartment unit, to test run the questionnaire and to assess the energy consumption in three different fields separately, viz. for lighting, for cooling and for general household activities. This helped to validate the questionnaire data with the electricity consumption bill and vice versa. Finally, a more extensive field survey was undertaken, based on this questionnaire in the randomly selected residential apartment units within particular residential areas, mostly inhabited by the middle income group in Dhaka city.

The following issues had been addressed in the prepared questionnaire,

- Size of the apartment unit
- Duration of occupancy
- Numbers and type of electrical appliances used for lighting, cooling and other household activities
- Running hours per day for each electrical appliance.

The following data had to be recorded directly by the surveyor during field survey,

- Electrical specification of the electrical appliances

- Physical properties of the study unit e.g. plan layout, site surroundings, day lighting and ventilation, building materials, orientation, solar exposure, opening sizes etc.
- Collection of the electricity bill of a calendar year.

The questionnaire was kept open-ended as the researcher had to fill it through a ‘Question and Answer’ session with the occupant of the study unit. This session revealed the answers related to duration of occupancy, comfort situation and uses of electrical appliances for various purposes. The electricity bills were collected, which helped to compare and validate, the amount of consumption calculated from the responses of the occupants, regarding their electricity consumption, gathered during the ‘Question and Answer’ session.

Before undertaking the full survey, a sample unit was studied in a randomly selected residential apartment unit at Uttara residential area to test run the questionnaire, and to assess the annual average electricity consumption for the separate sectors of lighting, cooling and household appliances. This outcome also helped to determine which sector is consuming more electricity, and in order for it to be given priority in considerations of energy consciousness.

The pilot survey revealed that, the average electricity consumption is higher in the winter months, than that of the summer months. This is due, mainly to the use of water heaters in winter, which is not used during summer months. Total average consumption of electricity in the different sectors of consumption found in the summer months is shown in Table 1,

Table 1: Electricity consumed in summer months by lighting, cooling and household appliances

<b>Sector</b>	<b>Consumption (KWh)</b>	<b>Percentage (%)</b>
Electrical Appliances for cooling	139.20	38
Electrical Appliances for lighting	34.57	10
Electrical Appliances for household	188.88	52
<b>Total Consumption</b>	<b>362.65</b>	<b>100</b>

It was found that, a significant 38% of electricity is consumed for cooling comfort, 52% of electricity is consumed by household appliances, while only 10% electricity is used for lighting purposes. Even though the percentage of household consumption may differ among different samples, it is clear that the percentage of electricity consumption for cooling is a substantial portion (second largest) of the total consumption, and it will be even higher, if any high electricity consuming appliances like air conditioner is used.

The calculated consumption data was found to agree closely with the electricity bills, having only nominal deviations of 9.2% in summer months and 3% in winter months. The test run therefore validated the questionnaire and methodology, and was consequently used for survey on a wider sample of 30 apartments.

The sample apartments were selected randomly from different planned residential areas in Dhaka city, based on some basic similarities in the aspects mentioned below,

- Located in planned residential areas
- South facing, as recipient of highest solar radiation and wind (Ahmed, Z. N., 1995)
- Third or fourth floor, i.e. 10-12m above ground

- Floor area within 93-148.7m<sup>2</sup> (1000-1600sft), as representative of middle income group (Labib et al, 2013).

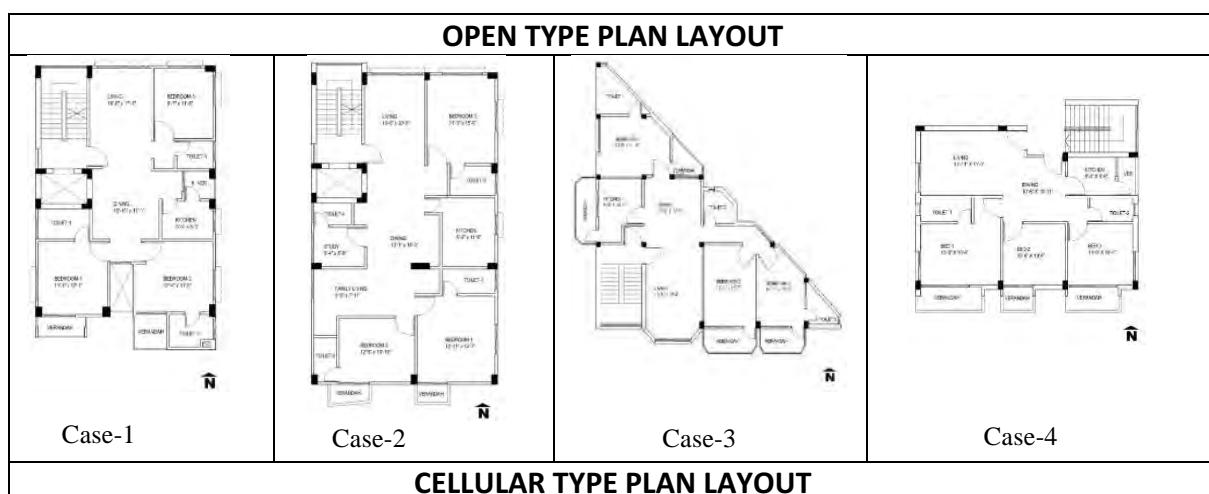
After the survey and collection of plans, they were analyzed. The samples were seen to belong between two basic types, depending on their layouts (Allen. T et al, 2004). The first type, where at least 25% of floor area is composed of living-dining open area, was classified as “open plan” layout. Where the living-dining open area was found to be less than 25%, the apartment was classified as having a “cellular” layout. Among the 30 case studies investigated during this phase, eight samples were finally picked for further detailed analysis, on the basis of the issues mentioned below, consisting 20% of total sample size,

- Availability of Complete Electricity Bill of a single year.
- Accuracy of the electricity bill, i.e. consumed unit and payable amount in BDT
- Long term duration and consistent occupancy in the apartment unit.
- Similarity of the consumption behavior by the users.
- Similarity in the physical building elements like opening sizes, depth of shading devices and room sizes

Of these eight samples, four plans were of the ‘Open type’ and four of the ‘Cellular type’.

## The Results

The floor plans were drawn during the survey of all study units (Figure 1). The plan layouts provide an insight of the functional zoning, spaces and their uses of each individual case. It also provides the information about the position and size of the openings. Understanding the typology of plan layout, along with size and position of the openings is important to find the relation between plan layout and its ventilation and day lighting situation, as these issues are associated to the overall electricity consumption by each apartment unit. These selected eight apartment units were situated at different locations of the city, having high demand for apartment ownership among the middle income group (Ahmed, Z. N., 1995). After detailed survey and questionnaire responses, a comparison among the eight samples was made, to establish whether the layout, and the average electricity consumption during summer months, had any noticeable relationship (Table 2).



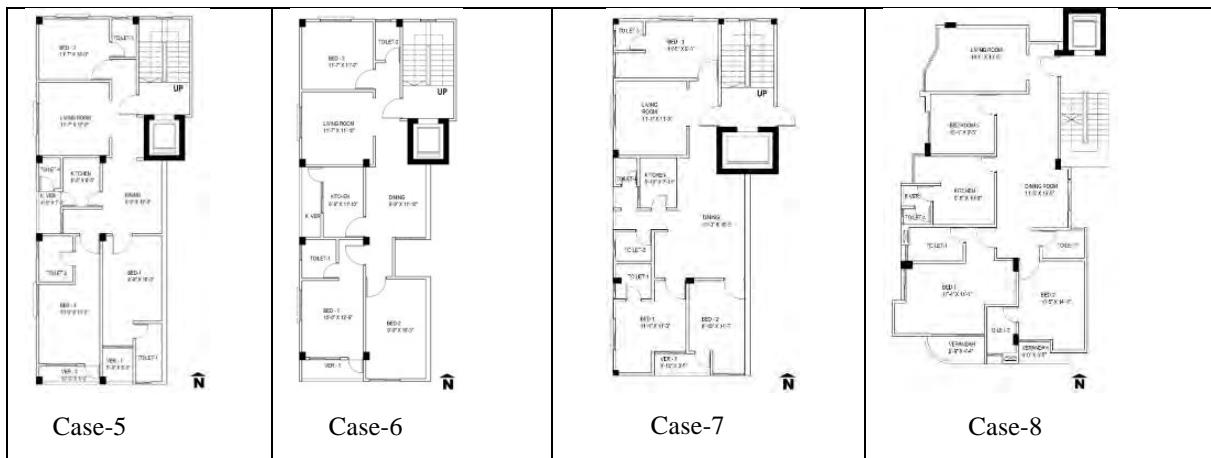


Figure 1: Open and cellular type plan layouts

Table 2: Relation between physical properties of building and electricity consumption

	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7	Case-8
Category	Open type	Open type	Open type	Open type	Cellular type	Cellular type	Cellular type	Cellular type
<b>Floor area (m<sup>2</sup>)</b>	100	137.5	121.7	101.2	108.7	104	101	119
<b>% of open area (living-dining area)</b>	29%	33%	25%	26%	15%	17%	23%	20%
<b>Verandah at south façade</b>	2 nos.	2 nos.	2 nos.	3 nos.	2 nos.	2 nos.	1 nos.	2 nos.
<b>Number of openings at south</b>	3 nos.	2nos.	3 nos.	3 nos.	2nos.	2nos.	2nos.	2nos.
<b>Size of openings at south</b>	1.5 x 2.0 1.5 x 2.0 1.0 x 2.0	1.5 x 2.0 1.5 x 2.0 1.5 x 2.0	1.5 x 1.37 1.5 x 1.37 1.5 x 1.37	1.5 x 2.0 1.5 x 2.0 1.5 x 2.0	5' x 6'6" 5' x 4'6" 1.5 x 1.37	1.5 x 1.37 1.5 x 1.37 1.5 x 1.37	1.5 x 2.0 1.5 x 1.37 1.5 x 1.37	2.5 x 2.0 2.5 x 2.0 1.5 x 2.0
<b>Total Window area (m<sup>2</sup>)</b>	25.35	26.95	15.33	20.95	15.65	16.72	18.0	22.67
<b>Window-floor area ratio</b>	25.3%	19.6%	12.6%	20.7%	14.4%	16.0%	17.8%	19.0%
<b>Average electricity consumption in summer months (KWh)</b>	399	197	186	176	602	607	805	298

Summary of the findings from Table 2 are as follows,

- The amount of electricity consumption does not depend on the size of the floor area. Larger floor area having open type layout was found to be more efficient in terms of electricity consumption than smaller floor area having cellular type layout.
- Percentage of open area, which combines living and dining as an open area, seems to have impact on electricity consumption. The ‘open type’ of apartment, with the central dining-living area being, more than 25% of total floor area, was found to consume less electricity in three of the four case studies.
- Verandahs on south façade often provide good shading. It is seen to create a buffer zone between the exterior and interior, and protect the room from getting direct solar exposure during the day. In cases 6 and 7, Bedroom-2 was found to be exposed to direct solar radiation, due the absence of any verandah, resulting in the use of air conditioning, and consequent high average electricity consumption in the summer months.
- Among the ‘open’ type of apartments, Case 1 with the highest amount of openings on south façade had the highest consumption, compared to the other three studied cases.
- Window to floor area ratio does not seem to have any significance on electricity consumption. Case-1 having 25.35% window: floor area ratio, seems to consume more electricity than Case-3, which has only 12.6% as its window: floor area ratio, though both Cases belong to the ‘open type layout’. Cases 5, 6, 7 and 8, all representative of ‘cellular type layout’, were all found to have less than 20% of window: floor area ratio, with high electricity consumption.
- It was found that, the “open” layout (Cases 2, 3 and 4) consumes less electricity during summer months, than the “cellular” type (Cases 5, 6 and 7). Cases 1 and 8, however, showed close consumption figures, though belonging to different layout groups.
- It was also found that, Cases 5, 6 and 7 consume almost three times more electricity in summer months than Cases 2, 3 and 4.
- The occupants of Cases 5, 6, 7 and 8, having cellular layouts, all use air conditioners for thermal comfort in the summer months. It is an indicator that, using ceiling fans is not adequate to ensure thermal comfort, in apartment units having cellular layouts, resulting in the increased electricity consumption in summer months.

In general it can be concluded from this investigation that, open layouts consume less electricity in the summer months. The reason for this may be that they permit the generation of indoor air flow, due to unobstructed open space.

Later a CFD study was conducted to visualize the indoor air movement due to natural ventilation, as it is associated with the thermal comfort of the occupants, and can form a passive design strategy.

#### ***CFD simulation of the selected samples***

The wind flow pattern depends on layout type, and can be checked through simulations. CFD simulation, done in Ecotect 2011, provides a visual outcome of the wind flow situation as well as rate of wind flow. For the purpose of the simulation, outside wind speed was considered as 2m/s at 10m level flowing from the south (Ahmed, Z. N., 1995). The simulation outcome of wind flow given in Figure 2 was only considered for qualitative

assessment, and to generate an understanding of the indoor air flow pattern. For the purpose of this simulation, windows were considered as fully open and doors were also considered open to find indoor airflow under maximum open condition.

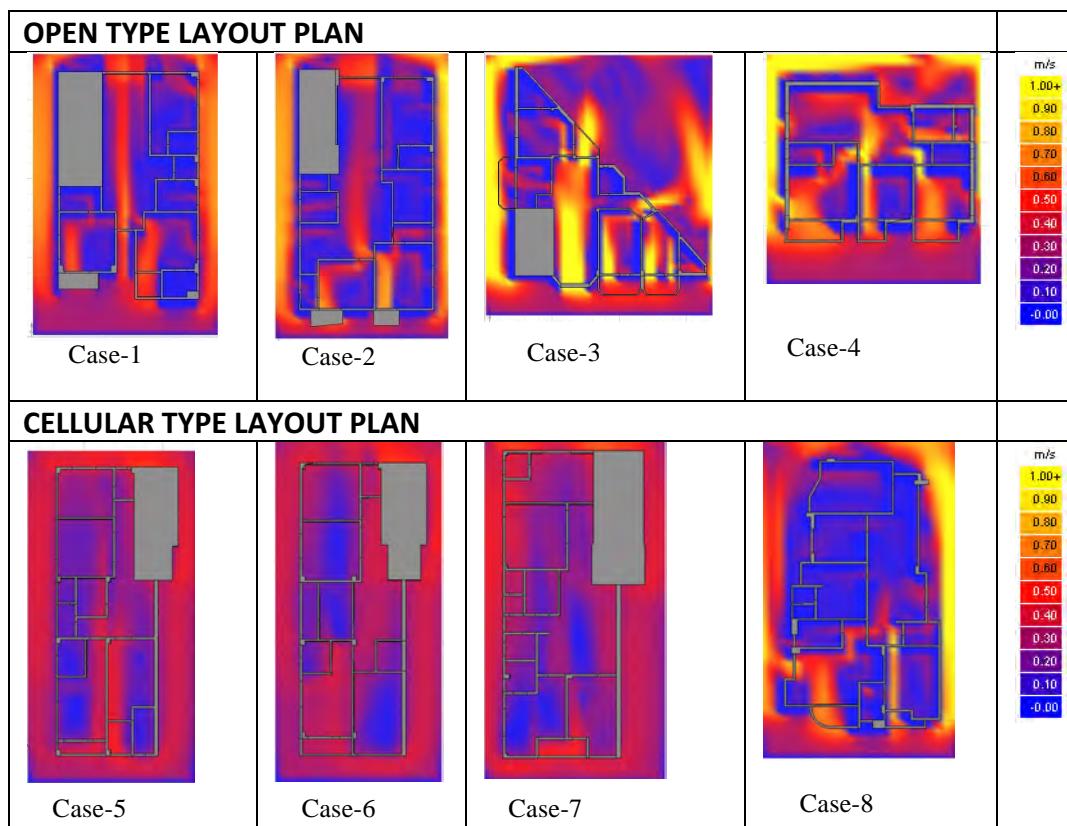


Figure 2: Wind flow simulation of selected samples

Figure 2 reveals that, in the open type layout plans, average indoor airflow through indoor spaces remains between  $0.5\text{--}1.0\text{ms}^{-1}$ , and most of the bed rooms get natural air flow. But, average indoor airflow through indoor spaces remain between  $0.2\text{--}0.4\text{ms}^{-1}$  in cellular type layout plans, which is much lower. Most of the areas in cellular type plan layouts have almost no indoor airflow. Moreover, Orange to yellow areas define the wind flow zones, which are seen to penetrate the plans in the open plan layouts (Cases 1 to 4), while they remain confined in the cellular layouts.

### Conclusion

In this research, the electricity consumption in the apartment units inhabited by middle and upper-middle income group were studied to find whether plan layout had any significant impact on electricity consumption for the purpose of cooling comfort. Both qualitative and quantitative aspects of plan layout, building elements and consumption data were analysed to investigate the impact of plan layout on electricity consumption in apartment units. The results revealed a significant relationship between plan layouts and related electricity consumption for cooling comfort.

Considering the significant amount of electricity consumed by the residential buildings in general and the prevailing electricity crisis in Dhaka, it is important to adopt reasonably simple energy efficient design features, that translate into less consumption of electricity for thermal comfort. The findings from the study suggest that, by adopting “open type” layouts

in apartments designed for the middle and upper-middle income group, there can be significant reduction in electricity consumption for cooling comfort in the summer months. Moreover, “Open type” layouts also allow better indoor airflow, which ensures greater thermal comfort.

## References

- Ahmed, Z. N. (1995), Assessment of Residential Sites in Dhaka with respect to Solar Radiation Gains. unpublished PhD thesis. DeMontfort University; Leicester, UK.
- Allen. T, Bell. A,Graham. R, Hardy. B, Swaffer. F. (2004). Working without Walls. Office of Government Commerce, London.
- Annual Report 2012. Dhaka Electric Supply Company Limited (DESCO).
- Islam, N. (2004). The poor's Access to Land and Housing in Dhaka. World Bank.
- Labib, S.M. et al (2013). Location and Size preference for Apartments in Dhaka and Prospect of Real Estate Market. Bangladesh Research Publications Journal, Vol.9, Issue: 2, pp. 87-96.
- Smart Living Handbook. 4th Edition, May, 2011, pp 64-68.
- Tariq, S.H. (2016). An Investigation on Energy Consumption for Thermal Comfort with Respect to Plan Layout of Residential Apartment Buildings in Dhaka, M. Arch. Thesis, (unpublished) Department of Architecture, Bangladesh University of Engineering and Technology, Dhaka.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## User-oriented Design Strategies for Well-being Working Environments

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**Abstract:** Predictions of office building energy use have often varied significantly from the actual energy consumption by failing to account for adaptive occupant behaviour (AOB) or the lack of it. This paper presents the findings of recent research on environmental issues of office buildings in Madrid. A design guide was produced based on field measurements, simulation studies and literature survey. The design guide was applied to study refurbishment options for an existing building, an abandoned fully glazed tower built in the 1970s in central Madrid. In its present state, the building has high space heating and cooling loads and suffers from highly uncomfortable indoor environmental conditions. The paper illustrates the potential for creating sensible working spaces in free-running buildings that meet inhabitants' needs enhancing their experience and AOB.

**Keywords:** Well-being, comfort perception, working environment

### Introduction

Predictions of office building energy use often vary from actual energy consumption by failing to account for adaptive occupant behaviour (AOB). Previous studies suggest that the application of motivational strategies to enhance AOB can reduce energy consumption by 10-30% (Judd, K. S., et al 2013). Offering adaptation strategies to achieve comfort in physiological and psychological terms (Isalgue, A., et al, 2006) can lead to improvements in employees' health, job satisfaction, well-being and productivity. Strategies proven to be effective include:

- Environmental information to help inhabitants better understand their environment (Malone et al. 2013).
- Atmosphere that differentiates the ambience of diverse spaces (McElroy, et al, 2010) enabling inhabitants to choose where they would feel most comfortable (Levin, H., 2003).
- Adaptive buildings that enable the inhabitants to control and customize their environments (Nicol, F., 2001). However an excess of control might be problematic (Bordass et al, 1993) overstimulating the occupants (Baker et al, 1996).

This paper presents the findings of a recent research project that looked at environmental issues of office buildings in Madrid. The project focused on the case study of an abandoned office building built in the 1970s in central Madrid (Torrubia-Aznarez, J., 2016).

## Context and Climate

Madrid's winters are mild, summers are hot and dry (fig: 1). The average annual air temperature is 14.5C, with daily fluctuations of 9-14K which and good potential for nighttime in summer. Solar radiation is fairly high throughout the year with average daily global horizontal irradiation values of 2.0-7.6 kWh/m<sup>2</sup>.

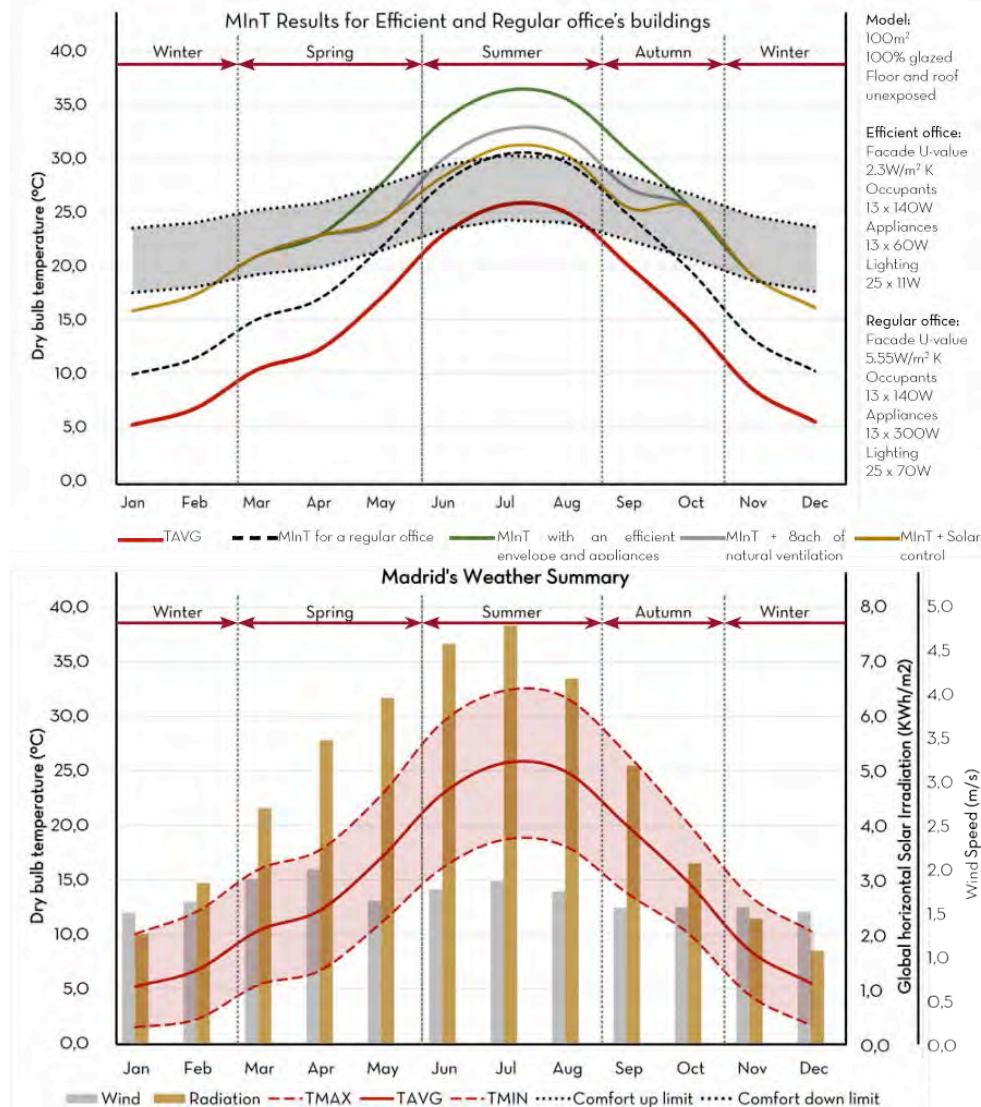


Figure 1: (Top) Comparison of outdoor air temperature with the predicted Mean Indoor Temperatures (MInT) of conventional typical office buildings and improved design with more efficient envelope and appliances. (Bottom) Madrid average weather data (Source: Torrubia-Aznarez, J., 2016)

## Indoor Environment (Working Space Design)

In studying the refurbishment of the case study building, different activities (working at a desk, informal meeting, coffee break, etc.) were carefully considered in relation to occupant environmental requirements and the likely indoor conditions in different parts of the building (Torrubia-Aznarez, J., 2016). A map of environmental conditions was created along with a study of the above requirements for each office activity (fig: 2). An internal distribution was proposed based on this information (fig: 2). Activities with lower internal gains and sporadic schedules (e.g. break areas and lounges) were located on the mapped

"hot spots" and between activities with high internal gains and a permanent schedule (e.g. working stations). Working areas were placed in cooler spaces with more homogeneous conditions. Activities with very high internal gains and sporadic schedules (e.g. physical activity spaces) were placed in "cold spots" or with variable conditions. Healthy sunlight exposure was taken into account according to inhabitants' expectations for each office activity.

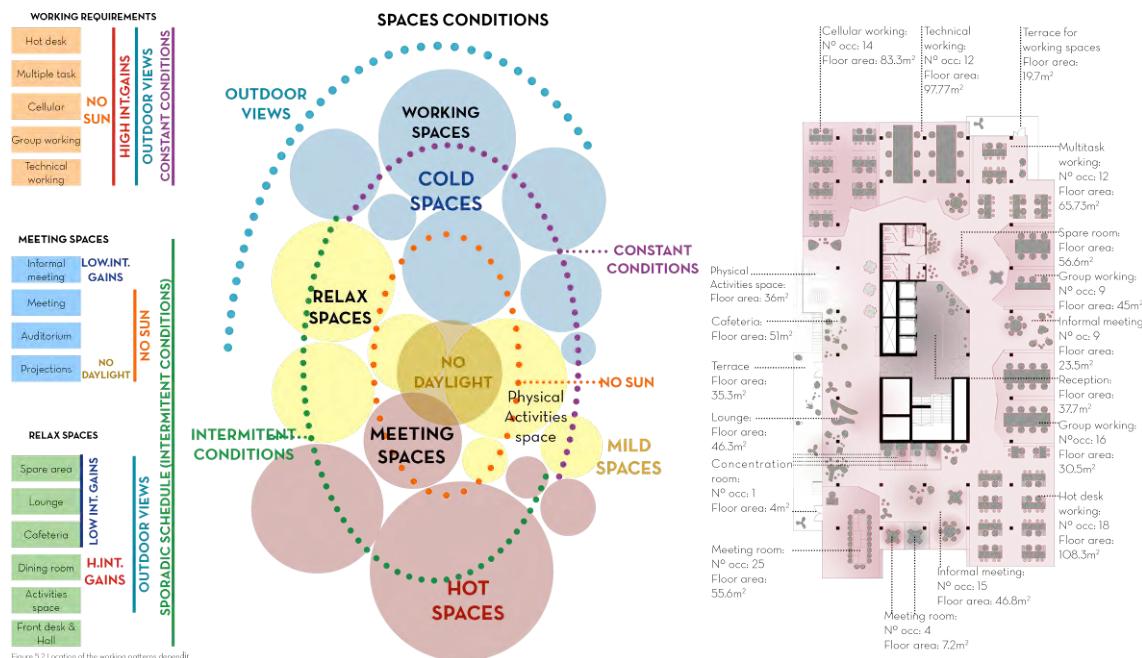


Figure 2: Left: Location of the working patterns depending on the internal conditions of the space to join them creating atmospheres. Right: 14th plan distribution. (Source: Torrubia-Aznarez, J., 2016)

The atmospheres of different spaces were designed to be accessible, adaptable and vibrant so as to create spatial familiarity and mindful design providing stimuli management and privacy.

### **Building Envelope**

The case study building, Torre Ederra (fig: 3), is an abandoned glazed tower of 22,700m<sup>2</sup> located in the "Azca" business centre. It is characterised by very low quality construction.

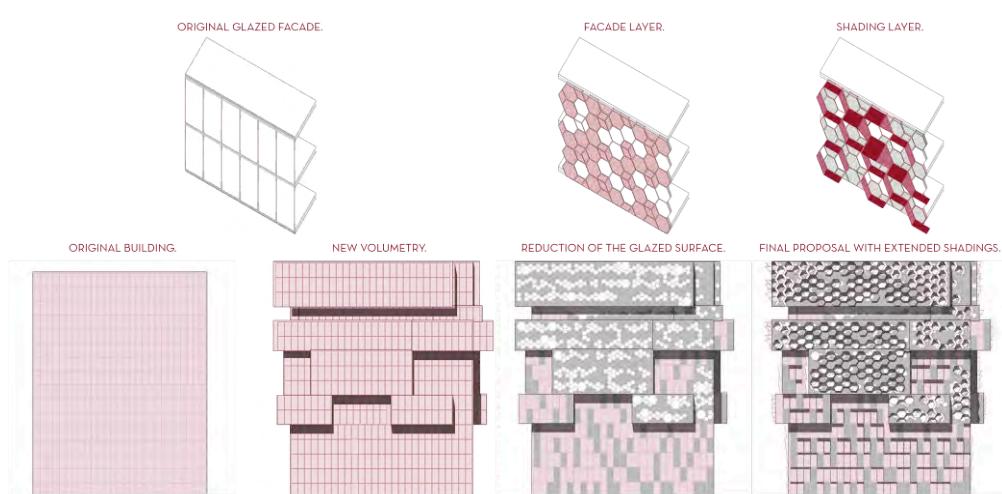


Figure 3: Evolution of the east elevation and layering. (Source: Torrubia-Aznarez, J., 2016)

For the refurbishment, materials were chosen to be sustainable and to ensure the required level of thermal and acoustic insulation. They are also expected to provide VOC reduction, and achieve appropriate reflectivity values for their purposes following well-being standards. Regarding structural elements of the construction the following are proposed:

- Exposing the concrete structure to take advantage of the thermal inertia
- Half of the elevators are considered excessive for this building and to be removed according to current national regulations.
- The façade to be replaced with modular adaptable double glazing units allowing the addition or removal of layers depending on seasonal conditions and climate change.
- On overshaded areas of the facades, the existing façade modules to be reused and adapted to the new system, achieving a 60% reuse and 40% recycled.
- The internal walls to be provided with green to obtain indoor biophilia advantages.

#### *Volume of the building*

The shallow plan of the building allows the floor plan to be extended to the limit of the passive zone. A series of protrusions are proposed on the façade to obtain some self-shading (fig: 4), wider working spaces and outdoor terraces. These should also increase the sense of well-being and facilitate maintenance of the façade.



Figure 4: Average annual solar radiation (Source: Torrubia-Aznarez, J., 2016)

Gardened areas on the terraces will help provide reductions in mean radiant temperature.

#### *Façade Layer*

A layer must be added to the façade for the control the solar gains and overillumination. The design of this layer is divided into three steps:

**Geometry:** A hexagonal pattern was chosen and tested for visual acuity, glare, solar protection and daylighting using Ladybug. The aim was to create a vibrant, modern atmosphere that would appeal to occupants' perception of an innovative and attractive work environment.

**Modulation:** Modules were sized to fit an operable window. Each floor will have three façade modules and two shading modules for better solar control and easier management.

**Percentage of transparent surfaces:** window to wall ratios were varied on the thermal simulations performed with EDSL TAS as shown in fig: 5 and table: 1 below.

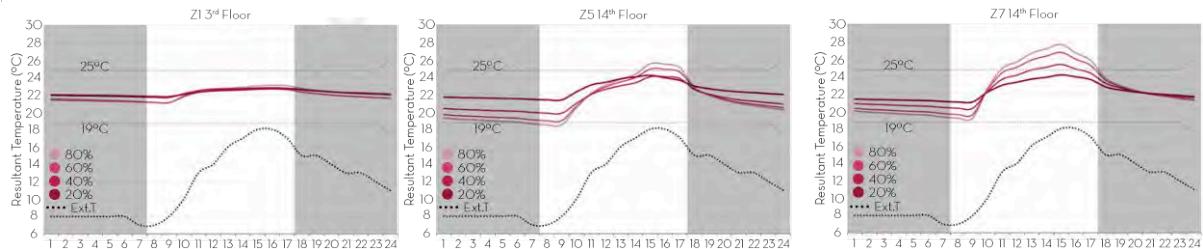


Figure 5: Temperatures during the 21<sup>ST</sup> of December for 20% 40%, 60% and 80% of glazed surface (Source: Torrubia-Aznarez, J., 2016)

Table 1: Percentages of glazed surface & correspondent transparent modules per zone (Source: Torrubia-Aznarez, J., 2016)

	Zone	Facade Area	% Transp.Facade	Transp.Area	Nº modules	Distribution	DAv inner part
EAST	Z1A	4.76m <sup>2</sup>	20%	0.95m <sup>2</sup>	1	Op1	100%
	Z1B	15.09m <sup>2</sup>	20%	3.12m <sup>2</sup>	3	Op 3	90%
	Z1C	14.85m <sup>2</sup>	30%	4.16m <sup>2</sup>	4	Op 3	80%
	Z4	75.4m <sup>2</sup>	30%	23.92m <sup>2</sup>	23	Op 3	55%
	Z6	42.32m <sup>2</sup>	15%	6.24m <sup>2</sup>	6	Op 3	55%
NORTH	Z1D	9.9m <sup>2</sup>	0%	0m <sup>2</sup>	0	Op1	100%
	Z1E	19.71m <sup>2</sup>	40%	7.28m <sup>2</sup>	7	Op 3	55%
	Z2	30.85m <sup>2</sup>	60%	18.72m <sup>2</sup>	18	Op 3	90%
	Z3	19.7m <sup>2</sup>	40%	8.32m <sup>2</sup>	8	Op 2	85%
WEST	Z3	34.65m <sup>2</sup>	20%	7.28m <sup>2</sup>	7	Op 2	90%
	Z5A	30.69m <sup>2</sup>	30%	8.32m <sup>2</sup>	8	Op 3	70%
	Z5B	44.71m <sup>2</sup>	30%	12.48m <sup>2</sup>	12	Op 2	90%
	Z8	46.45m <sup>2</sup>	13%	6.24m <sup>2</sup>	6	Op 2	55%
SOUTH	Z5	6.68m <sup>2</sup>	40%	2.67m <sup>2</sup>	3	Op 1	100%
	Z8	20.87m <sup>2</sup>	15%	3.12m <sup>2</sup>	3	Op 3	70%
	Z7	28.54m <sup>2</sup>	20%	6.24m <sup>2</sup>	6	Op 3	50%
	Z6	30.27m <sup>2</sup>	20%	5.2m <sup>2</sup>	5	Op 3	55%

Distribution of transparent surfaces: Three options were tested against a daylight availability target of 200 lux. The chosen option offers a wider variation in daylight conditions through the different spaces, higher lighting levels in the inner area and lesser risk of glare.

#### Shading

Excess solar gains, overillumination and glare issues were tackled with the addition of four types of shading devices. These were to meet a requirement for solar protection for vertical solar radiation values above 50W/m<sup>2</sup> (Reinhart, C.F., 2001). Solar radiation values below 40W/m<sup>2</sup> are allowed in the cold period. Most of the shading devices will be controlled by the inhabitants. Those located in areas that host activities requiring high levels of concentration or have a sporadic schedule will be operated automatically but with the option to override the system.

Daylight conditions met illuminance levels above 200 lux for more than 50% of working hours and the core above 100lux. Annual Glare metrics (DGP) showed positive results with momentary problems on the east and west facades during early mornings and late evenings. These situations can be tackled by using internal translucent screens.

#### Thermal comfort (operable modules):

The number of operable modules was set for each façade sector (Table: 02) according to indoor comfort conditions for the 21st of June. Some areas may reach 30C during warm

peaks (Fig: 6); ceiling fans were proposed for these areas. This strategy has a significant impact on occupants' perception of thermal comfort (decreasing thermal sensation by some 3K) and incurs little energy consumption (less than 2W/m3) (Isalgue et al, 2006).

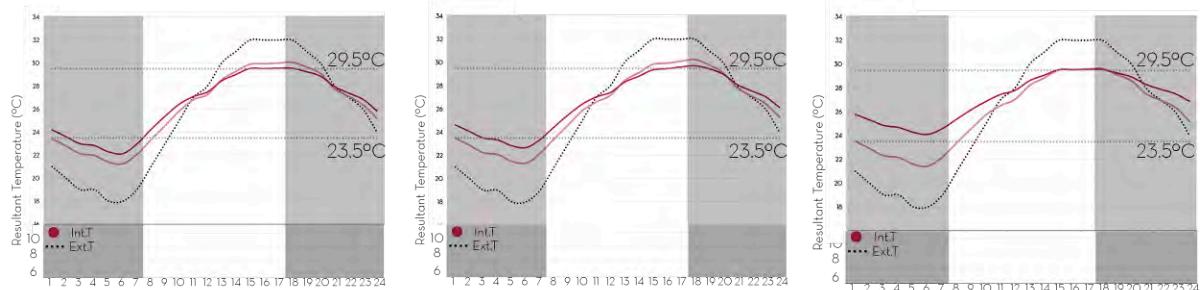


Figure 6: Temperatures during the 21<sup>ST</sup> of June for 20% 40%, 60%and 80% of operable surface (Source: Torrubia-Aznarez, J., 2016)

Table 2: Percentages of open surface & correspondent operable modules per zone. (14<sup>th</sup> floor) (Source: Torrubia-Aznarez, J., 2016)

	Zone	Facade Area	% OpenFacade	OpenArea	Nº modules	Max. Temp	Hours > 29.5°C
EAST	Z4	75.4m <sup>2</sup>	40%	30.16m <sup>2</sup>	37	29.2°C	0h
	Z6	42.32m <sup>2</sup>	20%	0.46m <sup>2</sup>	1	29.6°C	2h
	Z1A	4.76m <sup>2</sup>	40%	1.90m <sup>2</sup>	2	29.6°C	3h
	Z1B	15.09m <sup>2</sup>	40%	6.04m <sup>2</sup>	7		
	Z1C	14.85m <sup>2</sup>	40%	37.13m <sup>2</sup>	46		
NORTH	Z1D	9.9m <sup>2</sup>	40%	3.96m <sup>2</sup>	5	29.6°C	3h
	Z1E	19.71m <sup>2</sup>	40%	7.88m <sup>2</sup>	10		
	Z2	30.85m <sup>2</sup>	80%	24.68m <sup>2</sup>	30	29.5°C	0h
	Z3	19.7m <sup>2</sup>	60%	11.82m <sup>2</sup>	15	29.8°C	3h
WEST	Z3	34.65m <sup>2</sup>	60%	20.79m <sup>2</sup>	26		
	Z5A	30.69m <sup>2</sup>	40%	12.28m <sup>2</sup>	15	29.6°C	1h
	Z5B	44.71m <sup>2</sup>	40%	17.88m <sup>2</sup>	2		
	Z8	46.45m <sup>2</sup>	20%	9.29m <sup>2</sup>	11	29.9°C	3h
SOUTH	Z8	20.87m <sup>2</sup>	20%	4.17m <sup>2</sup>	5		
	Z5	6.68m <sup>2</sup>	40%	2.67m <sup>2</sup>	3	29.6°C	1h
	Z7	28.54m <sup>2</sup>	80%	6.24m <sup>2</sup>	8	29.6°C	2h
	Z6	30.27m <sup>2</sup>	20%	6.05m <sup>2</sup>	7	29.6°C	2h

The operable modules will be manually controlled by the occupants during the working hours. During the night hours an automatic system will manage them to obtain night cooling advances.

## Conclusions

The application of passive design strategies can create comfortable, free-running working environments. For the case study in Madrid the need for mechanical heating is eliminated (fig: 7), and the residual cooling loads or hours of overheating are very low (Table: 03). Sensible daylighting design reduced considerably the use of electric lighting. The remaining equipment and lighting loads may be met by 50% from PV panels on the facades and parts of the rooftop.

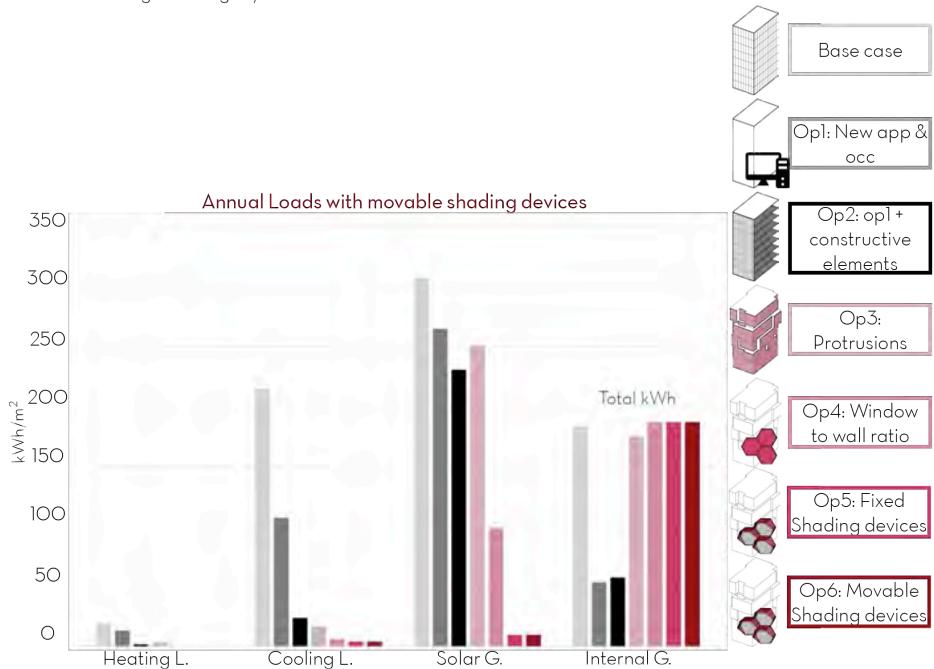


Figure 7: Annual Loads for Base case and options 1 to 6 (Source: Torrubia-Aznarez, J., 2016)

Table 3: Annual Loads and occupant density for Base case and options 1 to 6 (Source: Torrubia-Aznarez, J., 2016)

	BASE CASE	OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5	OPTION 6
Occupants (nº)	85	69	69	110	110	110	110
Surface (m²)	597	741	741	836	836	836	836
Heating Load (kWh/m² per year)	19	13	2	3	0.2	0.3	0.2
Cooling Load (kWh/m² per year)	214	107	24	17	6	4	4
Solar Gains (kWh/m² per year)	307	265	230	250	99	10	10
Internal Gains (kWh per year)	183	53	58	175	187	187	187

Further research is required for a better understanding of the occupant environmental requirements and well-being. The main issues to be researched are thermal perception fluctuations through the day, lighting conditions such as circadian effects, and variations in contrast levels to create interesting spaces that offer visual comfort.

## References

- Baker, N., M. Standeven (1996) Thermal comfort for free-running buildings. *Energy and Buildings* 23, pp: 175-182.
- Bordass, B., K. Bromley & A. Leaman (1993) "User and Occupant Controls in Office Buildings" In Proc. ASHRAE Conference Building Design, Technology and Occupant Well-being in Temperate Climates. Brussels, Belgium.
- Isalgue, A., M. Palme, H. Coch, R. Serra (2006) "The importance of users' actions for the sensation of comfort in buildings". In Proc. PLEA 2006 Conference.

Judd, K.S., M. Zalensky, T. Sanquist & N. Fernandez (2013). "The role of occupant behaviour in achieving net zero energy: A demonstration project at Fort Carson". *Pacific Northwest national laboratory*. Sponsored by US Department of Energy. Richland, Washington.

Levin, H. (2003) "Designing for people: what do building occupants really want?" *Proceedings: "Healthy Buildings 2003," Singapore, Singapore, December 2003*. Volume 1, pp. 11-28

Malone, E.L., R. Diamond, A.K. Wolfe, T. Sanquist, C. Payne & J. Dion (2013) "Implementing Sustainability: the behavioral-Institutional Dimension" *Sustain*. Issue 28- Spring/Summer, pp. 28-32.

McElroy, J.C., & P.C. Morrow (2010) "Employee reactions to office redesign: A naturally occurring quasi-field expersiment in a multigenerational setting." *Human relations*. Vol 63, num 5, pp: 609-636.

Nicol, J.F. (2001) "Characterising occupant behaviour in buildings: towards a stochastic model of occupant's use of windows, lights, blinds, heaters and fans". *Proceedings of IBPSA Conference Vol 2, International Building Performance Association*, pp: 1073-8.

Reinhart, C.F. (2001) "Daylight availability and manual lighting control in office buildings: simulation studies and analysis of measurements". Phd dissertation. University of Karlsruhe, Germany.

Torrubia-Aznarez, J. (2016). "Perceived Environments in Offices: The occupant's Comfort Perception as a Design Guide for Working Environments". MArch Dissertation. Architectural Association School of Architecture, London, United Kingdom.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainability of vernacular architecture as a basis for new popular housing projects in Arequipa, Peru

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**Abstract:** The aim of this work is to present an analysis about three vernacular houses (Churajón, Moral, and Chicha) from remarkable architectonic periods of the Arequipa city in Peru: Pre-Spanish, Colonial, and Republican. Some historic facts related with the region are presented in order to furnish a general panorama. This city is an oasis on the border of the Atacama desert, and aside there are three volcanoes, and it can suffer earthquakes. The bio-environmental equilibrium is fragile. Nowadays, due to the urban spread and the increase of the land price, the poor people go to live in the city periphery inside uncomfortable and fragile houses. It is observed an intense occupation of the meadow areas which are crucial to maintain the regional climate, food production, and the ecosystem. Fundamentals of social sustainability and bioclimatic architectures are employed in the analysis in order to create conditions to empower poor people and to protect the environment.

**Keywords:** Vernacular Architecture, Social Sustainability, Bioclimatic Approach, Arequipa

### Introduction

Nowadays, around the world the integration of the sustainability in the cities is a permanent challenge. (Bui, 2012) lists in this way some subjects to be considered by developing countries: urban demography growth, non-equilibrium urban-rural, land access, spontaneous housing, urban transport, environmental quality, healthy, education, people equity, cultural value and patrimony conservation. (Vallance et al, 2011) emphasize social aspect of sustainability and say: "we have highlighted the necessity of working through underlying conflicts and equitable and meaningful solutions to the problems confronting us". (Mora, et al, 2008) present some housing problems in Peru: (13.7%) dwellings built using precarious or non-desirable materials, (32.29%) dwellings not offering minimum living standards (electricity, sewage system, running water).

Arequipa, the second Peruvian city, has been engaged to apply some sustainable politics and strategies to deal with the divorce urban-territorial and environmental, pressure on peasant lands, meadow reduction, air and water pollutions, (Encalada et al, 2009). It is a fact that poor people lost ancient techniques and how to use local building materials, and then producing waste and pollution to the environment and indoor non-comfortable and fragile houses. From methodological point of view, (Rapoport, 1990) proposes for vernacular architecture an approach considering process and product, and emphasizes to learn by analysis. (Almodóvar et al,

2008) and (Almodóvar et al, 2012) dealt with the urban layout of Arequipa and the accessibility to solar energy, besides indoor temperature measurements in a colonial house. (López-Osorio et al, 2015) focused on the transformations of the Peruvian vernacular architecture as a result of the decolonization process and the recovery of original pre-Hispanic sources.

The intent of this work is to redeem some lessons from the vernacular architecture of Arequipa in three historical periods to examine the current relationship between the city and its low-income houses. Thus, is chosen a representative vernacular habitat from each of the three architectural periods in Arequipa: Pre-Hispanic, Colonial, and Republican.

### **The city of Arequipa**

Arequipa is an oasis city located in the South of Peru: 16° 24'10" South and 72° 32'10" West, see Figure 1. It has an altitude of 2329 m from the sea level, 280000 inhabitants and is crossed from North to South by the river Chili, (Ramírez, 2002). It is sited near three volcanoes of the Andes Mountains, and near the Atacama Desert and the Pacific Ocean. Besides the volcanic activities and earthquakes, there is a potential danger of melting ice on the Andes due to the greenhouse effect, therefore the ecological and environmental balances are fragile, (Llanque, 2003). From Figure 2 can be seen the yearly climate regularity in the region, the marked temperature differential between days and nights, and also the intense solar irradiation on a horizontal plane.



Figure 1. Localization of Arequipa. Source: (Ramírez, 2002).

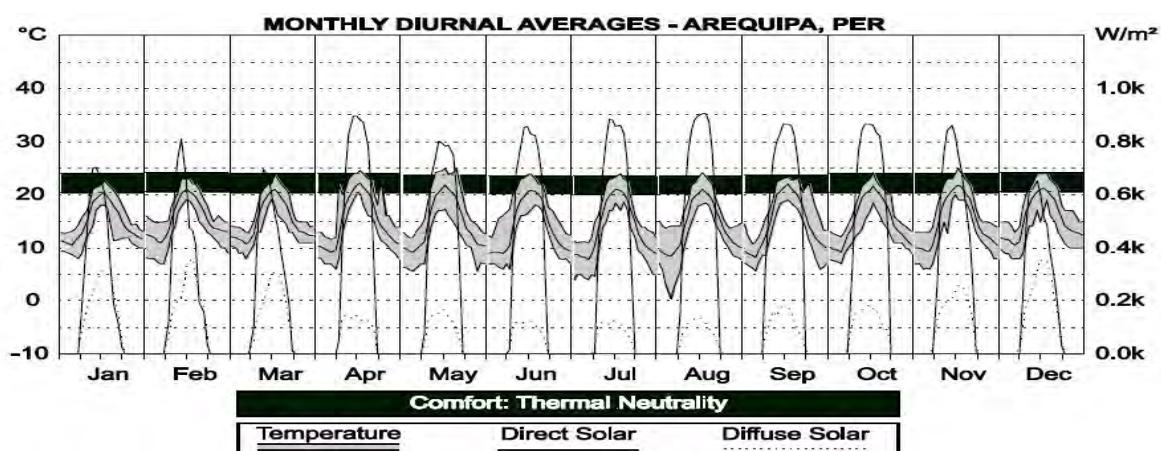


Figure 2. Climatic context of Arequipa. From (Almodóvar, 2012).

In the region, during the day there are predominant cool winds (temperature 20-25°C, relative humidity 25-55%) coming from W and SW. At night there are cold winds

(5 - 10 °C, 15-25%) from NE, Figure 3. Average wind velocity along the year is around 1.5 to 2.5m/s. According to the Givoni Bioclimatic Diagram, Figure 4, some strategies required for indoor thermal comfort in Arequipa are: passive and active solar heating, thermal mass, natural ventilation etc, (Llanque, 2003).

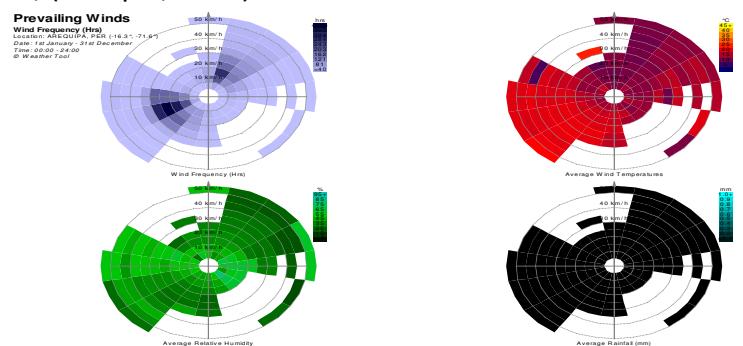


Figure 3. (from left to right) Yearly Average wind frequency, ambient temperature, relative humidity, rainfall.  
(Data processed from Rodrigues Ballón airport by weather tool 2011).

#### Psychrometric Chart

Location: AREQUIPA, PER  
Frequency: 1st January to 31st December Weekday Times: 00:00-24:00 Hrs  
Weekend Times: 00:00-24:00 Hrs  
Barometric Pressure: 101.36 kPa  
© A.J.Marsh '00

- SELECTED DESIGN TECHNIQUES:**
1. passive solar heating
  2. thermal mass effects
  3. exposed mass + night-purge ventilation
  4. natural ventilation 20
  5. direct evaporative cooling
  6. indirect evaporative cooling

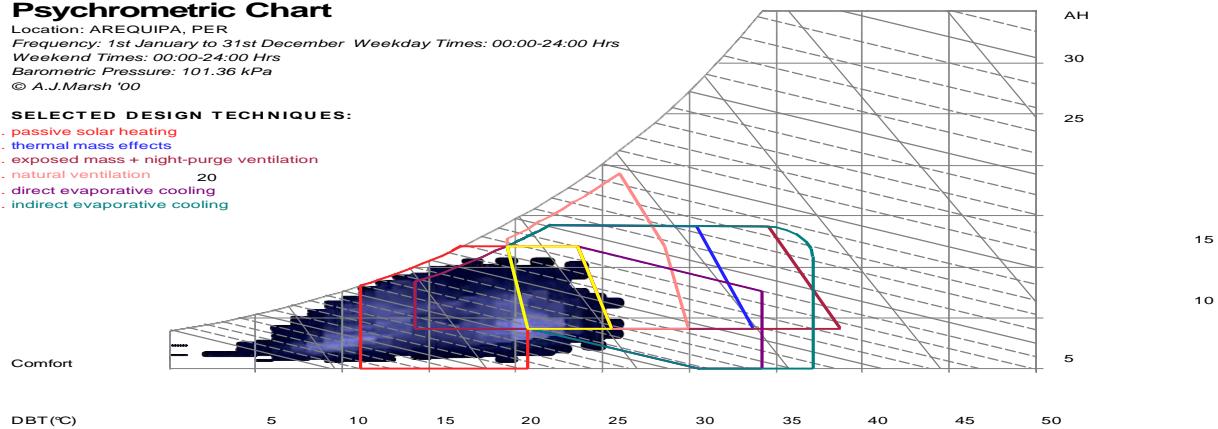


Figure 4. Givoni bioclimatic diagram of Arequipa

#### Arequipa Pre-Hispanic Vernacular (300bC to 1540)

Arequipa, from archaeological findings belonged to the Puquina (300bC - 500), (Bernedo, 1949). The economy was agrarian and pastoral. As time went on, there were a succession of ethnicities such as Tiahuanaco-Huari (500-1000), Churajón (1000-1450) and Inca (1450-1540). Along this period the habitat evolved from primitive subterranean shelters to houses of stone implanted with shape of a circle such as those found in archaeological sites of *Churajon* and Polobaya. Under the 90th years of Incas domination the economy was in agriculture, rebuilt and expanded the build (introducing adobe and straw); built villages and improved waterworks and agriculture.

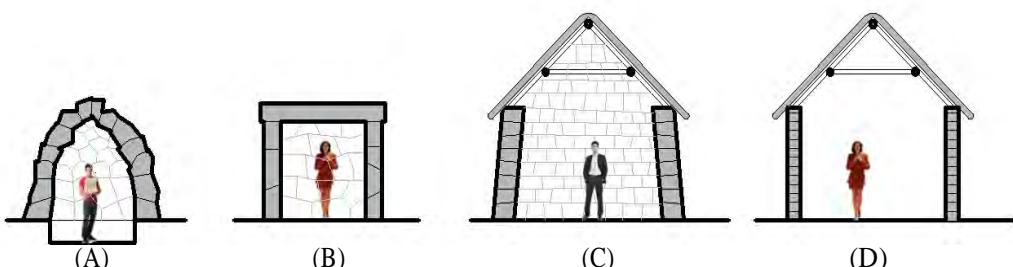


Figure 5. Scheme of the vernacular construction processes in Arequipa. (a) primitive house from Puquina, Huactalacta ruins in Pocsi. (B) Tiahuanaco and Huari houses. (C) Churajón house (D) Inca house. Source: Adapted from (Bernedo, 1949).

The cultural process influenced the architecture, which evolved over time adapting and increasingly better to this geographical environment, through new techniques and local materials. The worldview of these cultures also restricted the use of stones from the volcanoes because they were deities (iconographies and mummies were found in the PichuPichu volcano). The Arequipa meadow and the terraces on the hills (andenerias), Figure 6, are areas recovered from the desert by these Andean ancestors with works of hydraulic infrastructure and formation of the fertile ground for cultivation.



Figure 6. Arequipa meadow and andenerias. Source: raptravel.org

The vernacular habitat chosen as representative is the *Churajón house* (dated 1200). The house major axis is NE-SW (azimuth 45° from the North) contributing to maintain on the façade North a solar radiation almost constant along the year of 2.5 kWh/m<sup>2</sup>. Also, the location of the rooms is around a courtyard allowing the sunshine in most of the facades, which store energy by its mass, a convenience due to the temperature fall at nights. The plots follow an organic and irregular form adapting to the sloped terrain. The mountain blocks the cold winds. The house rooms are around a courtyard. Local stones as andesitic and granitic were used for walls (30-40cm thickness), a straw pitched roof, and very small fenestrations, (Álvarez, 2000). See Figure 5 and more ahead Tables 1 and 2.

#### ***Arequipa Colonial and beginning of the Republic: Vernacular by synthesis (1540-1945)***

The Peruvian ancestors had a long architectural and urban tradition, thus under the Spanish domination they contributed to a new expression of synthesis between the tradition and the coming Spanish models. This process occurred through an appropriation, (Burga, 2010). The sillar volcanic stone was used as a building material for the vaulted roofs and double walls favoring indoor thermal comfort and protection against earthquakes. All architectural expressions from this extended period are named vernacular by synthesis. *Proto-Spanish* (1540-1600): foundation of the city and social adaptation; earthquakes; agriculture and mining economy; incipient riverside houses; clay, trunks and straw; volcanic stone (sillar) in the portals of the churches. *Baroque* (1601-1700): earthquake; Vice-reign; autochthonous labor building process; century of religious buildings with sillar. *Neoclassical* (1700-1800): earthquakes; agriculture and mining; technology from religious buildings transferred to civil architecture; house layout changes; iconographic with religious content, but also with pre-Hispanic Andean motifs (baroque-mestizo); Del Moral house. *Neo-Renaissance* (1800-1900): earthquake; transition and independence of Peru (1821); exportations and textile industries, expansion of the urban fabric and people migration from neighboring cities. *Mixture of styles* (1900-1945): earthquake recovery; war with Chile; eclectic architecture, historicist, art decô, duke, neocolonial.



Figure 7. Panorama of the colonial historic centre of Arequipa. Source: skyscrapercity.com

The Neoclassic *Moral House* (1750) is chosen as the vernacular representative of this period. The orientation of the colonial urban plot follows an azimuth of  $20^\circ$  from North, parallel to the river Chili. This house has a central courtyard with a tree in the center, and is made of the white volcanic stone named sillar (walls and vault roof), and presents small windows. Nowadays this building is a museum, Tables 1 and 2. The NE-SW streets receive the cold night winds, and NW-SE streets the fresh daytime winds. The open inner courtyard provides ventilation during days and nights. The rooms mostly occupy the façade oriented to the daytime winds, and at night cold winds are incident on the service rooms. Also, at night, the bedroom doors were closed to conserve the ambient air heated and to reduce cold night air currents.

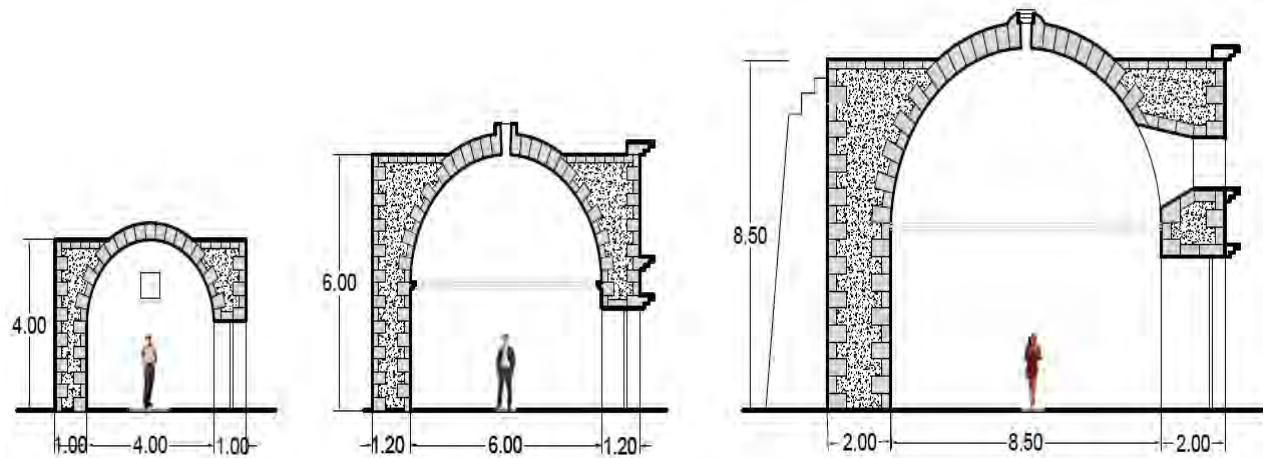


Figure 8. The vernacular by synthesis, building escalate processes in Arequipa. (a) Popular house;(b) High income house (c) Church. Source: Adapted from Bustamante, 2006.

### **Arequipa Republican: Modern, Postmodern, Modern Vernacular (?) and Contemporary (1945 - 2015)**

The period *Modern* (1945-1980): two earthquakes; informal economy; illegal work; public works for migrants; urban growth on the edge of the Misti volcano; higher incidence of migrant population due to industrialization; height growth of buildings; new avenues and popular urbanizations. *Postmodern* (1980-2000): high inflation; imports increase; informal markets; field-city migratory flow; search for cultural identity; trafficking and terrorism. Chicha Architecture. *Contemporary* (2000-2017): economic growth through mining; mix of cultures and customs; definition of middle and poor classes; neighborhoods; blend of architecture styles; majority of buildings of bricks, concrete and steel. During the 20th century and up to now, important buildings have been built following the international style, a tendency to be changed face the climatic and environmental conditions.

A popular architecture named *Chicha* (1980-2017) is considered as representative of this period, because it was born under marginal circumstances, poverty; process of “andeanizing” the city as an attempt of cultural decolonization of previous decades, a movement using native and mestizo symbols. Characteristics of low-income self-constructions, is a modern vernacular. Many authors like (López-Osorio et al, 2015) deal with the vernacular phenomenon, the “*Chicha architecture*” (so named because of Incan ceremonial drink made with fermented corn). This architecture uses symbolic elements of rural buildings in urban constructions as a mere representation, Figure 9. According (Burga, 2010) the Chicha architecture has a double code juxtaposing: rural and urban, vernacular and modern, ornamental and practical, historical and futuristic, provincial and metropolitan, traditional and current, artisanal and industrial. This architecture the immigrant erects in the city and summarizes a specific iconography with elements more characteristics of an urban architecture, which will allow for him integration and adaptation more quickly, (Burga, 2010). The plots are rectangular and predominant the North-South axis and then receive part of the cool winds during the day, and at night the cold winds. The house layout is compact and the courtyard is sited in the rear of the plot. The structure is of reinforced concrete, and brick walls, (Chamfreau, 1988).



Figure 9. Picture of house façades from the Chicha architecture in Peru. Source: Arq. Jorge Burg Bartra

### **Low-income housing and sustainability**

Currently Peru is no exception among Latin American countries, while the conception of low-income housing is focused only on the economy, leaving aside the other dimensions of sustainability. The sustainable architecture conception requires a multicriteria approach at where architectonic criteria (Spatiality, Materiality, Morphology, and Implantation) are crossed to the conditions to be attended (harmonious relationship with your environment, water and wastewater management, indoor comfort, etc), (Barroso et al, 2012).

It is estimated that 70% of houses are produced informally, which implies non-formal occupation of urban space, building without professional assistance, and the use of poor quality materials (IEC, 2015). The social housing program "Mi Vivienda" promotes the access of houses to low-income families with financial credits. The construction of buildings is designated to private real estate. Most of them are simple housing modules that are repeated without considering the implantation, orientation, etc, the materials have not quality, location in the city periphery (low cost land).

According to the national program, Arequipa currently has a deficit of 86,817 dwellings, generating problems such as the informality in the traffic of land, where groups of people gather to invade state or private lands as a response to a poor planning face to the urban sprawl.

Table 1 Localization in Arequipa of the vernacular typologies analysed. Source: author

	Churajón house, (before Spanish)	Del Moral house, colonial	Chicha house - contemporaneo
Pictures			
Building implantation sites	<ul style="list-style-type: none"> <li>Churajón house (Cerro Colorado)</li> <li>Similar typologies to Churajón house (Cerro o Pica)</li> <li>Del Moral (Historic centre)</li> <li>Chicha house (Polavayl)</li> </ul>		

Table 2 Urban vernacular typologies analysed. Source: by the author.

Churajón	Del Moral	Chicha
Churajón complex	Foundation feature, historic Center of Arequipa	Upper structure, Cerro Colorado
Plot distribution		
Ground floor plant		

## Conclusions

The analysis performed reveals that the low-income housing in Arequipa is a problem evolving the sustainability in its broad sense. People and city are actors interfering on the fragile environmental equilibrium of this region. Also there are social problems as poverty, lack of housing and social segregation. Aside are the natural impacts from volcanoes and earthquakes. The ancient inhabitants create conditions to be well adapted through adequate shelters, agriculture, and grazing activities. The Churajón house is a vernacular good example: correct implantation, high wall thermal inertia, two ways cover, advantage from topography and the fresh daily winds, use of local materials. From the colonial period the vernacular Moral house is well adapted to the environment: good plot implantation,

building with sillar, domed covers, new rooms layout, central courtyard, high wall thermal inertia, small windows. Concerning the vernacular modern Chicha, there is a setback due to the urban periphery occupation, face the urban swelling up and increasing land price, danger to meadow destruction, and pollution of the rivers. The sited plots and houses are not adequate to capture solar energy, the fresh daily winds, and are thermally uncomfortable. Also, there is the use of industrial materials not suitable for indoor comfort, and producing too much waste. Thus, Arequipa is behind time, it will be necessary to implement the Agenda 21 local, focusing on application of the sustainability tripode searching to solve the real problems lived by people and the city.

## References

- Almodóvar, J.M., Jiménez, J.R. (2008). Spanish-American Urbanism Based on the Laws of the Indies: A Comparative Solar Access Study of Eight Cities. Proceedings 25<sup>th</sup> Conference on Passive and Low Energy Architecture (PLEA), Dublin, Ireland.
- Almodóvar, J.M., La-Roche, P., Ramón-Jiménez, J., Dominguez, I. (2012) Learning from the Past: Environmental aspects of the traditional architecture of Arequipa, Peru. PLEA2012 – 28<sup>th</sup> Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima, Perú 7-9 November.
- Álvarez,P. (2000) La arquitectura y la distribución espacial del poblado prehispánico de Parasca (Polobaya) Arequipa. Universidade Católica de Santa María.
- Barroso, C.K., Bastos,L.E.G., SANTOS,C. NIEMEYER,L., SALGADO,M., ZAMBRANO, L.A. (2012). Princípios de Alta Qualidade Ambiental Aplicados ao processo de seleção de projetos de Arquitetura: O Laboratório Nutre. Vols. Volume 7, Número 1 . São Carlos, Brazil: Revista Gestão e Tecnologia de Projetos.
- Bernedo,M.L. (1949) A cultura Puquina. Ministerio de Educación del Perú. pp. 35-49.
- Bui, T.U. (2012) L'intégration du développement durable dans les projets de quartiers : le cas de la ville d'Hanoi. Thèse doctorat de l'Université de Toulouse.
- Burga, J. (2010) Arquitectura vernácula peruana: Un análisis tipológico. Lima. Colegio de Arquitectos del Perú.
- Chamfreau,M. (1988) La vivienda de los pueblos jóvenes de Arequipa y Trujillo. Lima. Buletim Instituto Francés. IFEA.
- Encalada,S. (2009) Estrategia ambiental urbana en Arequipa. In: Encalada,S. Zucchetti,A., Peralta,M. SCP/LA21 en Perú. Serie estrategias de apoyo a la gestión urbano ambiental. GEO cities UN Habitat, 28pgs.
- IEC. Arbulú R. (2015) Informe económico de la construcción. Vol. Número 5. CAPECO.
- Lihanque,J. (2003) Efectos de la contaminación atmosférica en el clima urbano y calidad ambiental de Arequipa. Universidad Nacional de San Agustín. Arequipa.
- Lopes-OSorio,J.M., Vizcara,G.R., Codes,U.M.(2015). Architectures in transformation in Peru: Tradition and modernity. In: Vernacular Architecture: Towards a Sustainable Future - Mileto,V., Garcia,S. & Cristini (Eds).pp.443-448. @2015 Taylor and Francis Group, ISBN978-1-138-02682.
- Mora,A.G., Calvo,P.C. (2008) House finance mechanisms in Peru. UN Habitat.Nairobi. 50 pgs. Pastor,P. (2014) Historia de la Arquitectura v.6, Universidad Nacional de San Agustín.
- Ramirez,C. (2002) Equipo AQPLAN21. Plan director de Arequipa Metropolitana 2002-2015. Municipalidad Provincial de Arequipa, 2002.
- Rapoport,,A.(1990). Defining vernacular design. In: Vernacular architecture: paradigms of environmental response. Turan Mete(ed.). Green Publishing Company Limited. Aldershot, England..pp 67-101.
- Vallance,S., Harvey C., Perkins,H.C., Dixon,J.E. (2011) What is social sustainability? A clarification of concepts. *Geoforum* 42 (2011) pp. 342–348.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Variability of human behaviour in outdoor public spaces, associated with the thermal environment

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**Abstract:** This paper presents part of the outcomes of a programme of research into the influence of the thermal environment on human behaviour in an outdoor public seating area. The research was conducted during one month in summer, autumn and winter of 2015 and 2016. The data gathered consists in the conduct of people using a public square in Nottingham city centre, and measurements of the environmental conditions taken at that place. The data of *Number of People* and the *Size of Groups* of people, were analysed according with the thermal environment of the place. The results showed a strong significant correlation between *Number of People* and *Globe Temperature\_sun* [ $r = .66, p < .001$ ]. A multiple regression analysis found that the *Number of People* per minute in a public space can be predicted using the *Globe Temperature\_sun* and the *Wind Speed* data of that place [R-square of .39,  $p < 0.001$ ]. These prediction models can be used to forecast the occupancy of the place and the grouping of users under different environmental conditions. The results can assist the design of urban spaces by allowing testing their future use with predicted data of human behaviour. In addition, the data obtained will serve as a foundation for further research about the human behaviour in public spaces.

**Keywords:** Human Behaviour, Outdoors, Number of People, Thermal Environment

### Introduction

The study of human behaviour in outdoor urban spaces has become a field of interest, due to the need to guarantee the wellbeing, leisure, socialisation, and general outdoor activities for "...3.5 billion people that live in cities" (Carmona, 2014, p.5). In the case of countries with seasons, the complexity of urban design is even greater due to the constantly changing environmental conditions which constitute additional variables to be taken into account.

The study of human behaviour in outdoors permits collection of valuable information about how people use public spaces and how this is affected by environmental conditions. Empirical observation of users in public spaces has been conducted by several authors over the last five decades. For instance, Gehl Architects developed observational studies since 1960's regarding the occupancy and activities in different cities across the world (Gehl & Svarre, 2013). According to Gehl, the quality of the physical environment affects the use of the space, as necessary activities will occur despite the quality of the space, for example going to the school or shopping will always happen despite the characteristics of the built environment. However, optional or spontaneous activities, such as: standing around or sunbathing, are more likely to appear under physical conditions which favour those activities, this is because "...place and situation now invite people to stop, sit, eat, play, and so on" (Gehl, 2011, p. 11). Furthermore, the studies conducted by Space Syntax since 1980's (2007) are focused in the connectivity between the built environment and social activities. In the study

*Calculation of Areas of Permanence in Public Spaces, According to Solar Radiation Simulated Conditions* (Waldron & Salazar, 2013), the simulated environmental data was used to predict behaviour, but without validated data.

These social and empirical studies conducted over the last decades have addressed the impact of the thermal environment over the behaviour of the user. However, synchronising human and environmental data remains as one of the challenges in this field.

Majority studies exploring human behaviour and environmental factors had focus in comfort of users (Nikolopoulou, M. & Lykoudis, S., 2006, Stathopoulos et al., 2004, Soligo et al., 1998, Bröde et al., 2012, Nikolopoulou, 2004). It is known that people are in constant interaction with the environment by adapting themselves or modifying the space around them to achieve their desired condition, *"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Nicol et al., 2012). For instance, adding or removing clothes to gain or lose temperature is known as an adaptive behaviour in indoors and outdoors.

The studies of comfort in outdoors have addressed the thermal perception of users, but *"A truly holistic basis of assessing pedestrian's satisfaction would, however, also consider sociological factors"* (Robinson, 2012). Since integrating the social variables to predict behaviours, or, studying the physiological human response to environmental conditions, by itself is insufficient. We need to look at the influence of social factors, as well as, their influence on the behaviour. Therefore, this research is focused on finding the relationship between different environmental conditions and human behaviour, and determining whether it is possible to predict the behaviour associated with certain thermal conditions.

This research will contribute to understand the human behaviour, its variability and relationship to the thermal environment. The collected data evaluated Number of People, Group Size, Time of Permanence, Body Postures, Activities and Adaptive Actions. However, this paper will present some of the main findings in the analysis of *Number of People* and *Groups' Size*.

## Method

The place selected to conduct the experiment was Trinity Square in Nottingham city centre. This public square was selected because it is typically occupied by different type of users (in terms of age, gender, occupations, activities, among others), it possess a constant pedestrian flow, it is a medium size square (suitable for camera capture) and it encourages people to use various types of public furniture, which allows different postures, from leaning to laying down.

The data was gathered during summer and autumn 2015 and winter 2016, in order to register the broadest range of environmental conditions of Nottingham. The study was conducted for four weeks in each season, recording three hours every day, which were randomly selected between 10:00am and 6:00pm.

A video camera was placed in a discrete position in order to avoid disturbing the normal use of the square. The environmental station was also placed in a discrete position, but located to ensure that the sensors were measuring the same environmental conditions as perceived by the users. The environmental station was therefore adjusted to head height of a person sitting.

Of the data gathered, one week for every season was analysed, making sure to include all the days of the week. However, the days selected were not sequential. When one day

presented exclusion, the next day was selected. The exclusion criteria were established to limit the sample to ordinary conducts of human behaviour in public spaces.



Figure 1 – *Left*: Photo of Trinity Square. *Right*: Sketch Plan view with the location of the Environmental Station, Video Camera and Area Evaluated.

This experiment was approved by the Ethics Committee from the Faculty of Engineering from The University of Nottingham. In compliance with the ethical considerations of the study, a poster was placed beside the camera explaining the purpose of the experiment and providing contact details of the author. The poster explicitly stated: *"Upon your request, we will not analyse any data related to your presence in the square. For this, or if you have any other questions about the study, please contact..."*

While studying natural environments, conditions may occur which cause changes in the behaviour, which are not solely explained by the influence of the thermal environment. These kinds of conditions have been excluded and therefore, the following events were excluded from the sample: rainy days, days with wet surfaces or extraordinary urban activities such as fairs.

The video data collected was coded to identify and classify the behaviours. The video analysis was divided to code two different kinds of behaviours:

The *Social Behaviour* consisted in observing the occupancy of the square and the type of group sizes. The sample size was 3779 minutes, corresponding to 21 hours per week, each season. The analysis of this data was done using a matrix in Excel, registering the *Number of People* per minute in the square and the number of *Groups of 1 person*, number of *Groups of 2 people*, number of *Groups of 3 people* and number of *Groups of 4 or more people*, per minute in the square.

The *Individual Behaviour* analysis consisted in registering the behaviour per person. The sample size is 3957 users observed remaining during the recorded period. This information was analysed with *Observer XT*, using a coding scheme previously designed and validated. At the end, the behavioural data was compared with the environmental data doing correlations, multiple regression and survival analysis.

For the purposes of this paper, it will only be discussed some of the results of the *Social Behaviour* analysis.

## Results and Discussion

*Table 1* presents the summary of environmental conditions registered per minute over the three seasons. The ranges of *Air Temperature* varied between 5.1 and 27.1°C; the *Relative Humidity* registered varied between 37% and 91%; the *Wind Speed* varied between 0 and 4.9 m/s and the *Light* levels oscillated between 12 to 27313 lx.

Table 1 – Environmental Data. N = 3779 minutes.

*Statistics (N = 3779)*

	Ta (°C)	rH (%)	Tg_sun (°C)	Tg_shad (°C)	Tr_sun <sup>1</sup> (°C)	Tr_shad (°C)	Va (m/s)	Light (lx)
Mean	14.4	63	17.1	15.4	23.8	17.8	1.028	4306
Median	14.9	63	16.8	15.3	20.3	16.3	.893	2893
Std. Dev.	5.0	13	6.4	5.5	14.1	8.0	.858	4653
Minimum	5.1	37	6.1	5.9	2.6	6.0	0.000	12
Maximum	27.1	91	34.9	29.5	83.6	55.5	4.959	27313

Table 2 presents the correlations between the environmental variables and the *Number of People, Groups of 1, Groups of 2, Groups of 3 and Groups of 4 or more*.

Table 2 - Correlation between Environmental Factors and Behaviour: Number of People and Group Size.  
*Spearman's rho Correlations*

	NP	G1	G2	G3	G4+	Ta	rH	Tg_sun	Tg_shad	Tr_sun	Tr_shad	Va	Light
NP	Correl	1.00											
	Sig.												
G1	Correl	.71**	1.00										
	Sig.	0.00											
G2	Correl	.83**	.48**	1.00									
	Sig.	0.00	.00										
G3	Correl	.61**	.32**	.38**	1.00								
	Sig.	0.00	.00	.00									
G4	Correl	.56**	.20**	.28**	.20**	1.00							
+	Sig.	0.00	.00	.00	.00								
Ta	Correl	.61**	.49**	.50**	.36**	.30**	1.00						
	Sig.	0.00	.00	.00	.00	.00							
rH	Correl	-.13**	-.06**	-.14**	-.03*	-.09**	-.23**	1.00					
	Sig.	.00	.00	.00	.03	.00	.00						
Tg_su	Correl	.66**	.48**	.56**	.38**	.33**	.88**	-.29**	1.00				
	Sig.	0.00	.00	.00	.00	.00	0.00	.00					
Tg_sh	Correl	.63**	.47**	.53**	.38**	.32**	.97**	-.22**	.95**	1.00			
	Sig.	0.00	.00	.00	.00	.00	0.00	.00	0.00				
Tr_su	Correl	.57**	.43**	.48**	.33**	.29**	.71**	-.37**	.88**	.78**	1.00		
	Sig.	0.00	.00	.00	.00	.00	0.00	.00	0.00	0.00			
Tr_sh	Correl	.62**	.46**	.52**	.37**	.32**	.89**	-.29**	.94**	.93**	.93**	1.00	
	Sig.	0.00	.00	.00	.00	.00	0.00	.00	0.00	0.00	0.00		
Va	Correl	-.34**	-.21**	-.29**	-.21**	-.17**	-.05**	-.19**	-.24**	-.15**	-.06**	-.08**	1.00

<sup>1</sup> The *Mean Radiant Temperature* (*Tr\_sun* and *Tr\_shadow*) was calculated in accordance to BS EN ISO 7726:2001 by using the equation:  $Tr = [(Tg + 273)^4 + ((1.1 * 10^8 * Va^{0.6}) / (\epsilon g * D^{0.4})) (Tg - Ta)]^{1/4} - 273$ , where  $\epsilon g$  is the emissivity of the grey globe 0.95, and  $D$  is the diameter of the globe in meters 0.038.

Sig.	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Lx Correl	.55**	.34**	.45**	.35**	.34**	.52**	-.37**	.75**	.62**	.81**	.73**	-.29**	1.00	
Sig.	.00	.00	.00	.00	.00	.00	.00	0.00	0.00	0.00	0.00	.00	.00	.00

\*\*. Correlation is significant at the 0.01 level (2-tailed).

The highest correlations found between the human behaviour and all of the environmental conditions measured, were: *Number of People* and *Globe Temperature\_sun* [ $r = .66, p < .001$ ]; *Groups of 1* and *Air Temperature* [ $r = .49, p < .001$ ]; *Groups of 2* and *Globe Temperature\_sun* [ $r = .56, p < .001$ ]; *Groups of 3* and *Globe Temperature\_sun* [ $r = .38, p < .001$ ]; *Groups of 3* and *Globe Temperature\_shadow* [ $r = .38, p < .001$ ] and *Groups of 4+* and *Light* [ $r = .34, p < .001$ ].

As can be observed, *Globe Temperature* had a strong influence over *Number of People* and *Groups' size*. As reported by Nikolopoulou et al. (2001): “*It is clear that warm conditions and presence of sunlight are important factors in the use of the space*”. Conversely, *Relative Humidity* had a low or a nonexistent correlation with *Number of People*, and, and *Groups' sizes*. According to Nikolopoulou and Lykoudis (2006), the *Relative Humidity* is a parameter that has a relationship with comfort, but “*... people are not very good at judging changes in humidity levels, unless relative humidity is very high or very low*”. Therefore, since *Relative Humidity* is not a parameter that can be accurately perceived by people, its influence over the *Number of People* or *Groups' size* is low.

The highest correlation between human behaviour and the environmental conditions measured was *Globe Temperature\_sun* and *Number of People* [ $r = .66, p < .001$ ]. Figure 2 presents the scatter plot of this relationship. This table shows that during winter, the *Number of People* (blue dots in the scatter plot of Figure 2) started to increase dramatically when the temperature reached at least 13 °C, and continued increasing as the temperature became warmer. It must be however noted, that most of the data collected of *Number of People* in winter, corresponds to around 13 people or less at a time. During autumn and summer the occupancy tend to increase.

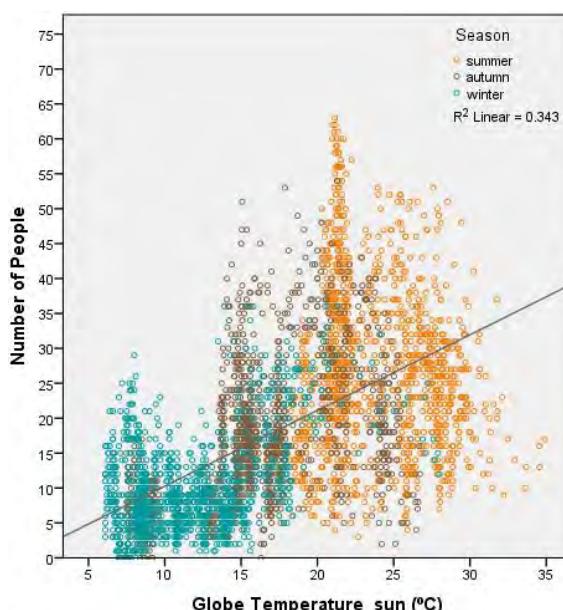


Figure 2 - Number of People and Globe Temperature\_sun. In colours are marked the data per season.

Interestingly, despite registering some of the same ranges of temperature in various seasons, the influence of the *Globe Temperature* over *Number of People* varied depending on each season. Whereas the range of 13-15°C was measured in winter and autumn, the *Number of People* in autumn was clearly higher at this temperature, than in winter.

The same phenomenon was observed in summer and autumn. Whilst both seasons had temperatures within the range of 18-19°C, the number of people at this temperatures was clearly higher in summer. This behaviour may be explained by the thermal history of people since the environmental conditions in indoors can influence the behaviour in outdoors.

The disparity observed between seasons may be also explained by the fact that we were only considering the highest correlation, but the body reacts to multiple stimuli simultaneously. Therefore, a multiple regression model including *Globe Temperature\_sun*, *Wind Speed* and *Light* was built to predict *Number of People*.

The regression analysis was conducted splitting the sample in two: 60% ( $N = 2064$ ) of the data was used to do the multiple regression analysis and 40% ( $N = 1715$ ) was retained for validation of the equations (Stevens, 2009). For the regression model, a *Forward* method was used. This method takes the highest simple correlation as the first predictor and then the highest semi-partial correlations to see the contribution of each variable inserted to the model. In the analysis, it was found that the *Light* didn't contribute to the model; therefore, it was discarded. *Table 3* contains the results of the model to predict *Number of People* based on the *Globe Temperature\_sun* and *Wind Speed*.

Table 3 - Multiple Regression Model to predict *Number of People*  
*Coefficients*

Model	Unstandard. Coefficients		Standard. Coeff.		
	B	Std. Error	Beta	t	Sig.
(Constant)	2.742	.703		3.897	.000
Tg_sun	1.027	.032	.563	31.827	.000
Va	-2.404	.255	-.167	-9.414	.000

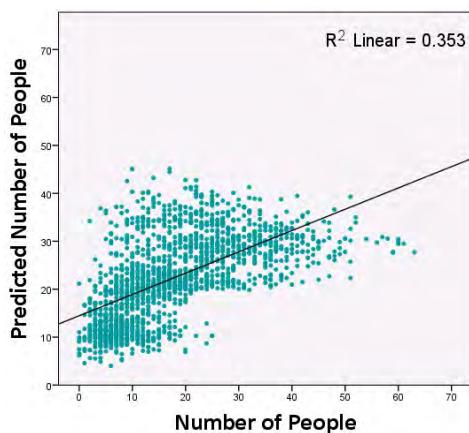
a. Dependent Variable: *Number of People*

The b-values (B in *Table 3*) correspond to the individual contribution of each predictor to the model [ $p < .001$ ]. Therefore, they were used for the regression equation:

$$\begin{aligned} \text{Number of People} &= b_0 + b_1 \text{Globe Temperature}_\text{Sun} + b_2 \text{Va} \\ \text{Number of People} &= 2.74 + (1.03 \text{Globe Temperature}_\text{Sun}) + (-2.40 \text{Va}) \end{aligned}$$

The *Globe Temperature\_sun* and *Wind Speed* account for the 39% of the *Number of People* [ $r^2 = .39$ ,  $p < .001$ ]. This means that the 39% of the *Number of People* is explained by the influence of these two variables acting simultaneously. The equation was tested with the 40% of data remaining and the results obtained are significant [ $r = .66$ ,  $p < .001$ ] (*Figure 3*).

Figure 3 shows the scatter plot of the number of people and the predicted number of people of the 40% of the date. It is observed that the model predicts up to 35% of *Number of People* using *Globe Temperature\_sun* and *Wind Speed*.



Spearman's rho Correlations			
		N_People	Predicted N_People
Num. of People	Correlation	1.000	.660**
	Sig.		.000
N		1715	1715

\*\*. Correlation is significant at the 0.01 level (2-tailed).

Figure 3 - Left: Scatter plot between predicted and real data. Right: Correlation Coefficients for Number of People and Predicted Number of People.

This method of analysis has been applied to *Group Size*, obtaining also significant results.

## Conclusions

The human behaviour is influenced by multiple environmental factors, acting simultaneously, because the body is a multi-sensory organism which adapts to the environment.

Number of People is influenced by Globe Temperature\_sun and Wind Speed. This was previously reported by other authors. Conversely, Relative Humidity does not influence the Number of People or Group Size.

Number of People and Group Size presented several correlations with various environmental factors, which could serve for further analysis. In this study, only the highest correlations were considered.

Globe Temperature\_sun and Wind Speed accounts for 35% of Number of People. The remaining percentage corresponds to other variable not included in this research, such as individual characteristics of the subjects.

Specific behaviours are influenced by different environmental factors. Globe Temperature affects Number of People, but the Air Temperature affects Groups of 1. This means that different statistic models are needed to predict different behaviours.

The validation of the model helps for its generalisability to be applied in different locations with similar conditions.

Further studies could be undertaken to assess the several possibilities of the data collected to predict the human behaviour.

## References

- Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B. & Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). International journal of biometeorology, 56, pp. 481-494
- BS EN ISO 7726 (2001). Ergonomics of the thermal environment – Instruments for measuring physical quantities. BS: London.
- Carmona, M. (2014). *Explorations in Urban Design: an urban design research primer*. Surrey: Ashgate Publishing, Ltd.
- Gehl, J. (2011). *Life between buildings: using public space*. Washington: Island Press.
- Gehl, J., and Svarre, B. (2013). *How to study public life*. Washington: Island Press.
- Nicol, F., Humphreys, M. A. & Roaf, S. (2012). *Adaptive thermal comfort: principles and practice*. Abingdon: Routledge.

- Nikolopoulou, M. (2004). Designing open spaces in the urban environment: a bioclimatic approach, Centre for Renewable Energy Sources, EESD, FP5
- Nikolopoulou, M., Baker, N. & Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy*, 70, pp. 227-235.
- Nikolopoulou, M. & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41, pp. 1455–1470.
- Soligo, M. J., Irwin, P. A., Williams, C. J. & Schuyler, G. D. (1998). A comprehensive assessment of pedestrian comfort including thermal effects. *Journal of Wind Engineering and Industrial Aerodynamics*, 77–78, pp. 753-766
- Stathopoulos, T., Wu, H. & Zacharias, J. (2004). Outdoor human comfort in an urban climate. *Building and Environment*, 39, pp. 297-305
- Robinson, D. (2012). *Computer modelling for sustainable urban design: Physical principles, methods and applications*. New York: Routledge.
- Stevens, J. P. (2012). *Applied multivariate statistics for the social sciences*. New York: Routledge.
- Waldron, J., & Salazar, J. (2013). Calculation of Areas of Permanence in Public Spaces, According to Solar Radiation Simulated Conditions. In *Design, User Experience, and Usability. User Experience in Novel Technological Environments*, 8014, pp. 215-223.
- Whyte, W. (1988). *City: Rediscovering the center*. Pennsylvania: University of Pennsylvania Press.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A survey on indoor comfort and energy consumption in a care home

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**Abstract:** This report presents a feasibility study carried out in a Care Home in Edinburgh from December 2016 to March 2017. The aim of the study is to test a set of methods to assess room comfort and energy efficiency. The methods consist of a literature review on indoor comfort for older occupants, a survey on both objective and subjective thermal & humidity comfort in 10 selected rooms and an energy performance assessment for the building. The review suggests an idea comfort zone of 22-24C and 45%-60% for older people in care homes. The objective assessment shows that less than 1% of the time the room hygrothermal conditions were within the suggested comfort zone. The subjective assessment carried out using a questionnaire survey reveals 70% of the subjects felt "warm" and "slightly warm" on thermal site and 30% voted "slightly dry" on humidity side. The energy assessment, using standard methods, shows that the care home had a fair energy performance when compared against national benchmarks for similar buildings.

### Introduction

Care homes are spaces that require a secure, warm and comfortable environment continuously throughout the entire year, making them energy and resource intensive. Their energy consumption was estimated about 2.4 million tons of CO<sub>2</sub> and £468.5 million for utility cost during 2008/2009 [Braddley, 2012]. Plus, the projected increase of the elderly population has called for prioritising energy saving in care homes and operation strategies to meet the challenge of achieving economic and environmental sustainable development [Sait, 2014]. Care homes in Scotland have a higher demand for space and water heating due to the cold climate in the UK, as its heating degree days is about 40% more than that of England. Therefore, to meet an elderly person's comfort temperature in Scotland requires more heating.

Dry skin is very common among older people and the major cause of discomfort, itch and even eczema, which has become a major problem of well-being in later life, especially during winter, when central heating results in dry room air. The common term "winter itch", generally experienced by average occupants tends to be more pronounced in the elderly, due the age-related dermatological conditions [Hurlow & Bliss, 2011]. But studies on thermal comfort have been focussed primarily on average healthy adults for either hot climate and free running buildings or older people response to temperature only. Consequently, there is no clear guidance on indoor hygrothermal (thermal and humidity) conditions; for the designer during the design stage or managers in daily operation of the buildings.

In summary, with a growing elderly population spending more of their time indoors and their increasing expectations of internal comfort levels, it is key to establish that these conditions are being met in order to reduce the chance of negative health effects and increase the quality of living for elderly people. Additionally, it is important that these conditions are met whilst using minimal energy due to the strain being put on Scotland to meet their 2050 green-house gases reduction target with increasing social, environmental and economic strain being presented to the world. It is for these reasons that the hygrothermal conditions within a care home setting and the resultant energy consumption of the building play a key role in the issue of this country's sustainable development.

As a feasibility study, the main aim is to assess the indoor hygrothermal conditions, personal comfort perception and energy performance in one care home and with a small sample. It was intended to prove a hypothesis - care homes are often too dry in winter due to high temperature setting in central heating. It was also expected to propose suggestions on environmental services provision and energy management. Due to no funding available at the time, this was carried out as an undergraduate dissertation project with intensive supervision input.

#### Objectives:

- To propose a comfort zone of indoor environment for older residents in care home based reviewing the national standards and current research findings
- To monitor the indoor environment over a winter season and then assess the condition against the standard and the research suggestions
- To conduct a simplified occupant survey on personal perception of their indoor environment
- To assess the energy performance and find possible ways for improvement: better energy efficiency and quality indoor environment

### The Methods

To achieve the aim three methods were applied: a literature review that established the indoor comfort standard for older occupants, an assessment on thermal & humidity comfort that compared the actual data against the standard, and an energy assessment that showed energy performance in the care home.

#### *The selected comfort zone in care homes*

The comfort conditions for average adults has been thoroughly examined and standards are well established and are commonly applied in design and management. On contrary, there is currently no specific standard for older people's hygrothermal comfort. To establish a comfort zone for older people, research was based on reviewing latest research papers together with the design guides issued by well-established organisations, CIBSE[2008] and ASHRAE[2007]

Comfort studies have been primarily focused on average healthy adults, or older people's response to only temperature [Rupp et al, 2015] or heat stress in summer [Mendes et al, 2015]. For winter comfort, studies only confirm that older occupants prefer a warmer indoor environment [Nigel A.S]. The reasons are summarised as follows:

- Immobility and lower activity levels leading to a lower metabolic rate
- Reduced body heat production caused by low metabolism
- Deterioration of the heat control system and thermoregulation ability
- Reduction in lipid under the elderly's skin

- Reduction in weight causing a lower metabolic rate and increased body heat loss

An experiment discovered that most older people feel comfortable at 23-27°C in summer and 20-25°C in winter. When averaged out, all of these figures create a range of approximately 22-25°C in summer and 21-24°C in winter for older people [Hwang & Chen, 2010]. But a recent study on the environmental impact of care homes for NHS East Midland suggests otherwise, to reduce the room temperature to 21°C for energy saving purposes [Braddley, 2012]. Such inconsistency is evidence for the need of a standard for older occupants.

Unlike thermal issues, there is very limited research specifically on the effects of room moisture on older occupants and so there is no clear guidance on optimal indoor hygro-thermal conditions neither for early design nor for daily operation of the building services systems. There are a wide range of suggestions on the relative humidity (RH) for elderly peoples: such as 45%-70% throughout the year by White-Chu & Reddy [2011], 40%-70% by CIBSE Guide A [2008] and 30%-60% for the “*vulnerable population*” (including older people) by ASHREA[2007]. Hence for both physically and physiologically need, the older people a comfort zone was set: 22-24C and 45-60%, a warmer and a narrow relative humidity range than the averagely-aged people in winter.

### ***Personal comfort perception***

To compare against the objective measurements, questionnaires are an essential tool for subjective assessments for users' perceptions and preference for room comfort. The most questionnaires for thermal comfort is the 'Lekert Question', in which questions are based upon a usually 7-points scale and the wording in questions is set by British Standard [BS EN ISO 10552:2001].

A common feature in these questionnaires is that all questions follow the same format taking the occupant minimal effort to complete as they only have to circle the applied answer, without having to think and use their own words. In this trial study, a very simplified one was used so that our subjects can understand easily without requiring assistance from staff. Furthermore, the questions were to remain factual in order to keep the survey as short as possible. It included two closed-format questions in a large print. Question 1 asks directly about if the occupant is thermally comfortable using the standard format from BS EN ISO 10552:2001. Question 2 was copied from the thermal question by replacing words related to thermal by those of humidity. This was expected to provide a definite answer about if the resident felt dryness of the room air.

### ***The building and rooms***

The care home is located in Edinburgh, Scotland, catering to the needs of 23 elderly women of which the residential home offers full time residence and catering. The two-story building consists of a Georgian house to the south, accommodating: a dining room, living rooms, offices and other activities rooms, and a new extension the north, purposely built for all bedrooms over two floors (Figure 1). Highlighted are the selected rooms for the assessment and occupants participated in the survey, with all measured communal areas located on the ground floor in the frontal quarters of the building.

The selection for monitoring of the room conditions was made that the residents of the rooms were all with no “cognitive impairment” and able to make own judgement on their room conditions. All participating residents completed the consent form allowing a

small sensor to be left in each of bedrooms to record hourly the temperature and relative humidity. There were 10 residents took part of this exercise.



Figure 1. The plans (total floor area 976m<sup>2</sup>) and the selected test rooms in the study

### **Modelling**

RdSAP (Reduced data Standard Assessment Procedure), the UK official method for measuring the energy use in residential dwellings was used for this study [BRE 2012]. The building was considered a joint of two semi-detached dwellings: one for the original build and the other for new extension and so, two separate RdSAP spreadsheets were used. This is due to the difference in use and varied construction methods for the two very different parts of the building.

The process ignored individualised patterns of occupancy, hereby the input required adaptation in order to cater to the needs of a care home occupancy in terms of density and hours as well as hot water consumption. This was carried out through manual calculations to work out the utilisation factor of the boiler and occupancy of which are manually entered to the RdSAP spreadsheet to ensure a more fitting and accurate output.

### **Energy performance**

The gas and electricity meter readings were obtained from management staff in order to assess the care home's overall energy output. As gas is used for cooking, heating and hot water and electricity for lighting, appliances and cooling, the CIBSE Energy Consumption Guide [CIBSE, 1996] breakdown was applied to the combined gas and electricity values across both years (2015 and 2016). As space heating and lighting are the factors that vary most per month, these factors will be calculated from taking the difference between the average meter reading value (between the two years) and the other factors that make up the energy usage such as hot water and catering for the gas consumption and appliances and refrigeration for electricity.

The results were also compared against a survey carried out over 52 care home homes, in which the energy performance is divided into "good", "fair" and "poor" categories [DOE, 1996].

## Results

Three parts of results are presented in comparison manner: 1 objective assessment on room hygrothermal condition, 2 subjective perceptions by the participants and 3 energy performance results.

### ***Comparing monitored data against proposal standards***

Figure 2 shows the variation in temperatures and relative humidity measured in the selected rooms in the care home, over all measured times for bedrooms and between the hours of 08:00 and 20:00 for the communal spaces (Conservatory, Lounge, Dining Room) as these are the times of use.

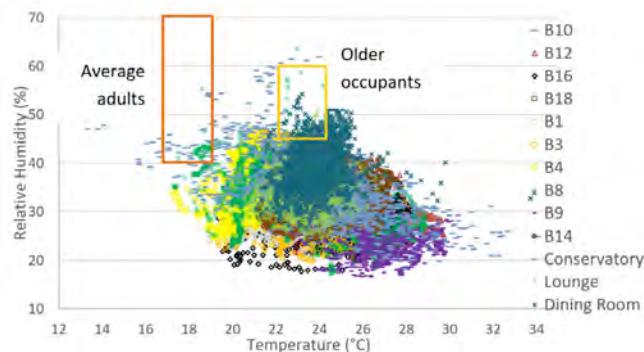


Figure 2. Measured data during frequently-used hours with two comfort zones respectively for average adults and old people

There were some moments when the room temperatures went below 17°C and beyond 30°C. These happened in the Conservatory. But great majority were between 18-26 °C, which is considered acceptable. The overall average temperature is 23.6°C, within the recommended comfort temperatures for older occupants at the high end of the recommended range. However, when the newly defined zone for the older occupants is applied, the vast majority of 99.2% of measurements are out-with the comfort zone (highlighted by the yellow box) and toward the overheating side.

On the other variable, the overall average of recorded relative humidity over the period was 33.2% and great majority were below the recommended low limit 45%. About 97.7% of the measured room humidity were out-with the comfort humidity level (low <45%) and over 87% lower than 40%, the lower limit for healthy adults. This strongly suggests the air in the care home is generally dry.

As the room air changes relative humidity reversely with its temperature, it is expected that the room humidity could rise 5% when the room temperature drops two degrees. There were many hours in some rooms the temperature was as high as 28-30 °C. If this could be reduced, it can be an easy solution to ease the dryness and improve comfort. Surely this "objective figure" should be considered together with subjective judgement from the short survey.

### ***Comparing the monitored data against personal perception***

Figure 3 shows the thermal comfort perception of each resident from the internal conditions of their bedroom obtained through questionnaires and compared to the objectively gathered temperature and RH measurements. These measurements are based on the percentages; calculated for below, within and above the recommended range for older occupants.

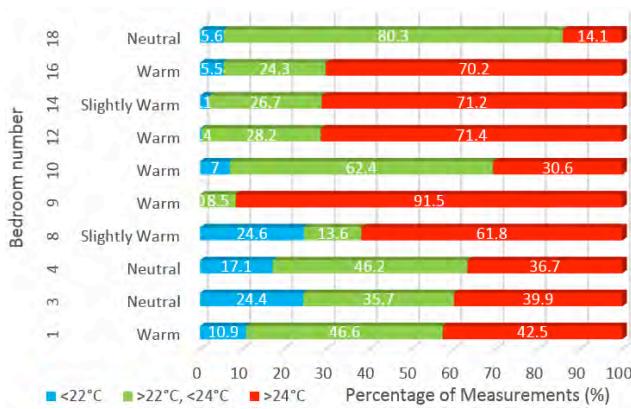


Figure 3. The room temperature vs personal perception

All bedrooms showing highs (>24°C) occurring for more than 24.8% of readings have answered that they feel on the warm side of the scale. The rooms with their occupants opted “warm” all had high percentage of measurements higher than 24°C. The three with “Neutural” had low percentage for high room temperature than 24°C. However, without questions on satisfaction and preference, like “would you like to be warmer or cooler” it would be difficult to decide if any attempt should be taken for improvement.

The other variable, the humidity shows to be low with most bedrooms showing that the majority of percentages below the recommended minimum of 45%. 3 of the 4 residents who answered ‘Warm’ for thermal perception correspondingly answered to find the environment ‘Slightly Dry’. Those who answered ‘Neutral’ for both questions appeared to have cooler bedrooms with slightly higher percentages showing to be <24°C with 60.1-85.9% of measurements below the recommended range. This would also lead to a small improvement on the humidity,

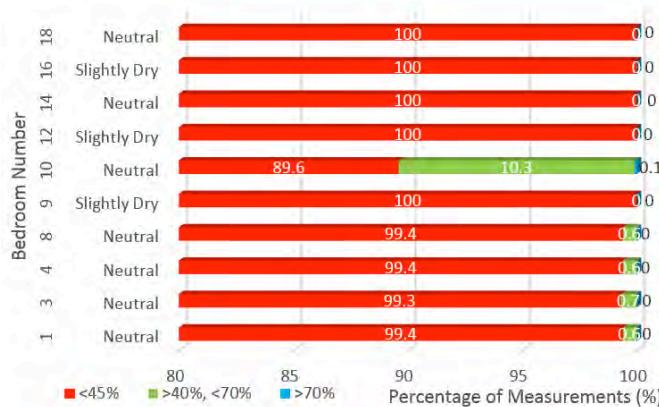


Figure 4. The relative humidity versus personal perception

Figure 4 reinforces how often the RH fell below the recommended lower limit of 45%. The only bedroom seeing more than 0.7% of measurements within the recommended range being Bedroom 10 showing 10.3% of measurements within the recommended range. Answers of ‘Slightly Dry’ shows 100% of measurements below 45%, also with 100% out-with. Interestingly only three of them felt “Slightly Dry”. Again like thermal aspect, it would be essential to add questions assessing their satisfaction and preference on the room humidity, if any change should be made to improve the humidity comfort.

## Assessment on Energy Performance

Figure 5 shows the collated data from benchmarks, RdSAP and the actual building consumption. Overall the care home energy consumption is good showing slight differences of approximately 1.5kWh/m<sup>2</sup>/year for 2015 and 12.1kWh/m<sup>2</sup>/year with the CIBSE TM46 national average. In terms of electrical consumption, the care home is over-consuming by approximately 20%. For gas consumption, the care home is performing well, using 11.4% less than the benchmark in 2015 and 7% less in 2016. This highlights a significant difference between the electrical and thermal fractions.

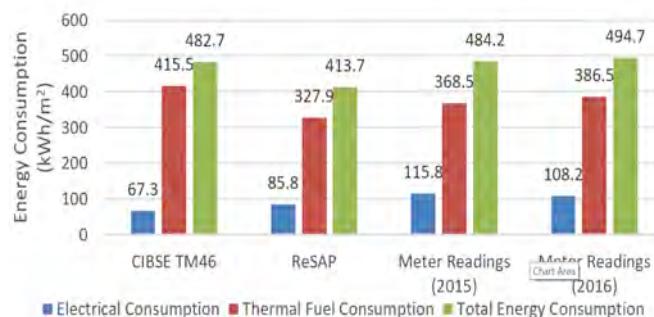


Figure 5. Meter readings, modelled & benchmarks

Both meter reading values show to be significantly larger in both electrical and fossil-thermal consumption when compared to the RdSAP value with differences of approximately 335,581kWh/year. This result is possibly more in line with a code of best practice standard of a care home with a fossil-thermal difference from the 2-year average of approximately 48,897kWh/year and an electrical difference of approximately 25,887kWh/year. Based on the gathered results, the benchmark comparison show that the build is in-line with the national average standards (CIBSE TM46).

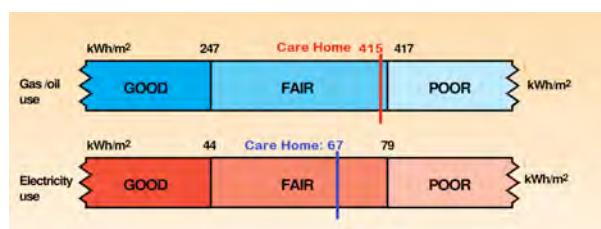


Figure 6. Comparison of the Care Home energy performance results against the best practice

A closer comparison in Figure 6 shows that the Care Home gas consumption was near the boundary between the “fair” grade and “poor” and the electricity was at the lower end of the “fair” grade. As mentioned before, the care home consists of a building that was built approximately 40-70 years ago and is now heating only for day activities and a newly purposely built for whole day heating. Hence it is not surprising it’s overall energy performance falls within the “fair” category.

## Conclusions

Based on the results and discussion of this study, we can draw up the following findings. Firstly, based on the review on both the current research and related national standards, 22-24°C for room temperature and 45-60% RH for relative humidity appear to have been endorsed as the hygrothermal comfort zone for the elderly population in care homes.

The objective assessment of a care home's indoor environment throughout a winter reveals that the care homes conditions do not meet the specified ranges in terms of either T or RH. There was less than 1% of the time the room hygrothermal conditions were within the suggested comfort zone.

The subjective assessment on the resident's perception of their room condition using questionnaires survey shows that most (70%) users found their environment on the warm side with some (30%) residents feeling the conditions were dry.

In terms of energy efficiency, the results show that the care home had a "fair" energy performance when compared against the national benchmarks for the similar buildings. The performance could be improved when the room temperature could be set 2 °C lower. As this was a simplified attempt, a full questionnaire survey would be able to provide a better view on the occupants' satisfaction and expectation on their room conditions. This could provide us with solid evidence for changing the set point for heating provision.

It further confirms that set of assessment methods could be applied to other care homes if the questionnaire could be revised by adding the questions that collect data on occupants' "satisfaction" and "preference" on room thermal and humidity conditions.

Finally, as the study as just trial and conducted in a small sample as an unfunded project, the findings are limited and reflect the condition of one care home only. Even though it does suggest that such exercise can provide evidence based data that is beneficial for scientific research for developing solid comfort criteria. It also provides feedbacks for management team in care homes to improve room quality and energy efficiency and cutting both environmental and capital costs.

## References

- ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers; Health care facilities/ chapter 7, HVAC application (SI), ASHRAE, 2007.
- Braddley J, Carbon, Cost and Care; Environmental impacts of residential social care in the UK, Nottingham: Nottingham Energy Partnership, 2012.
- BRE. The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2012 edition.
- British Standard BS EN ISO 10551:2001, Ergonomics of the thermal environment — Assessment of the influence of the thermal environment using subjective judgement scales, 2001.
- CIBSE, 1996. *Energy consumption guide for nursing and residential homes*, s.l.: Crown
- CIBSE, Energy Benchmarks TM46, 1st ed., London: CIBSE, 2008.
- CIBSE, The Chartered Institute of Building Service Engineering: Guide A: Environmental Design, London: CIBSE, 2008.
- Department of the Environment (DOE): Energy consumption guide for nursing and residential homes Energy Consumption Guide ECG057, 1996
- Hurlow J and Bliss D, "Dry Skin in Older Adults," *Geriatric Nursing*, vol. 32, pp. 257-262, 2011.
- Hwang R and Chen C, "Field study on behaviours and adaption of elderly people and their thermal comfort requirements in residential environments," *Indoor Air*, vol. 20, no. 3, pp. 235-245, 2010.
- Mendes S, Bonassi L, Aguiar C, Pereira P, Neves S, Silva S, Guimaraes R and Teixeira J, "Indoor air quality and thermal comfort in elderly care centers, urban climate.", *Urban Climate*, vol. 14, pp. 486-501, 2015
- Rupp RF, Vasquez NG & Lamberts R, "A review of human thermal comfort in the built environment," *Energy and Buildings*, pp. 178-205, 2015.
- Sait M, Care homes energy savings strategies are a priority in 2014, [www.savemoneycutcarbon.com](http://www.savemoneycutcarbon.com)
- White-Chu EF and Reddy M, "Dry skin in the elderly: complexities of a common problem," *Clin Dermatol*, vol. 29, no. 1, pp. 37-42, 2011.
- World Health Organisation, "Global Health and Aging," 2016. [Online]. Available: [http://www.who.int/ageing/publications/global\\_health.pdf](http://www.who.int/ageing/publications/global_health.pdf). [Accessed 16 Nov 2016].



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The effect of window form on thermal comfort in summer and in winter in the cold climate of China

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**Abstract:** There have been few researches discussing the effect of architecture elements on thermal sensation of humans. This study presents a series of experiments conducted in a climate laboratory to investigate the effect of window form on thermal comfort in the cold climate of China. The experiments were carried out from July to August 2016 and in January 2017 in a climate chamber, which was equipped with desks and chairs, etc., to simulate office environment. 64 subjects, mainly students aged from 18 to 26 without architectural background, were tested in summer and in winter, 32 for each season. Three window design parameters were selected as independent variables considering its visual characteristics, including: window-to-wall ratio (WWR), sill height (SH) and horizontal continuity (HC). Physical measurements of air temperature, relative humidity, wind speed, Carbon Dioxide and environment noise were measured. The experiments were conducted with the combination of natural lighting and artificial lighting, being controlled at 500lux. The results showed that WWR might have certain effect, while SH and HC have little effect, on thermal sensation.

**Keywords:** window form, window to wall ratio, sill height, horizontal continuity, thermal comfort

### Introduction

Comfortable thermal environment not only can create better environment for improving living and working conditions, but also has great benefit to the reduction of building energy consumption. Thermal condition, together with acoustical, luminous condition and indoor air quality, is important for evaluating indoor comfort. At present, the mainstream view of academia in this field is that thermal comfort can be affected by physical, physiological and psychological factors (Brager, 1998; Humphreys, 1998).

Window, as an important element of spatial interface, determines penetration, one of the five main features of space, the other four features being size, shape, material and colour of space. As provider of daylight and view, windows in vogue, bringing to the forefront of consideration by professionals in architecture, lighting, photobiology and psychology. Energy and environmental concerns and health and well-being goals each have brought renewed attention to the value of window as a matter of debate and discussion in both intellectual and practical lives of these fields, sharing a common goal of providing healthy built environment (Farley et al, 2001; Boyce et al, 2003).

The presence of window offers benefits through two dimensions of view: first, the effect of window on spatial appearance, particularly on the perceived spaciousness of room (Bruder, 2011; Hawkes, 2011; Collins, 1976; Farley & Veitch, 2001; Kaye & Murray, 1982; Butler & Biner, 1989& 1990; Kaplan and Kaplan, 1989; Stamps, 2004 & 2007; Stamps& Krishnan, 2006), since strong evidence has shown that for many (but not all) types and settings of room, people prefer window or skylight none due to the presence of window

making room look more spacious and reducing the feeling of enclosure; second, a view of outdoors, particularly if it is a nature view, offers benefits that are manifested as feelings, behaviours, and in physical health (Cohen, Kessler, & Gordon, 1997; Hartig, Mang, & Evans, 1991; Simons, Losito, & Fiorito, 1991; Kaplan, 2001), since clear evidence from laboratory studies and a variety of field investigations have shown the benefits of exposure to a view of outdoors, particularly nature views – although latter finding might be modified to consider the attractiveness of the view, whether natural or built.

From this background, it can be known that window has much effect on people's subjective perception of environment. To study the relationship between window and thermal comfort is necessary for improving living and working environment.

## **Experimental method**

### **Climate laboratory and subjects**

This study presents a series of experiments conducted in a climate laboratory (CL) in Tianjin University (Fig. 1). The building, with two floors, has good lighting and atmospheric conditions. There is multi-storey residence in the east with good landscape including trees and grasses. The study was conducted simultaneously in Chamber A and Chamber B respectively, which are of the same size of 12m (length) X 12m (width) X 9m (height), both towards east to prevent direct sunlight. Each chamber contains 36 windows, each window being 1.8 m wide and 1 m high. Totally 64 subjects including under graduate and postgraduate students participated in the experiments in summer and in winter, 32 in each season, and 16 in each chamber. All of them had already lived in Tianjin for at least two years and had adapted to Tianjin's climate. They were required to wear standard clothes as suggested. The figures are shown in Table 1.

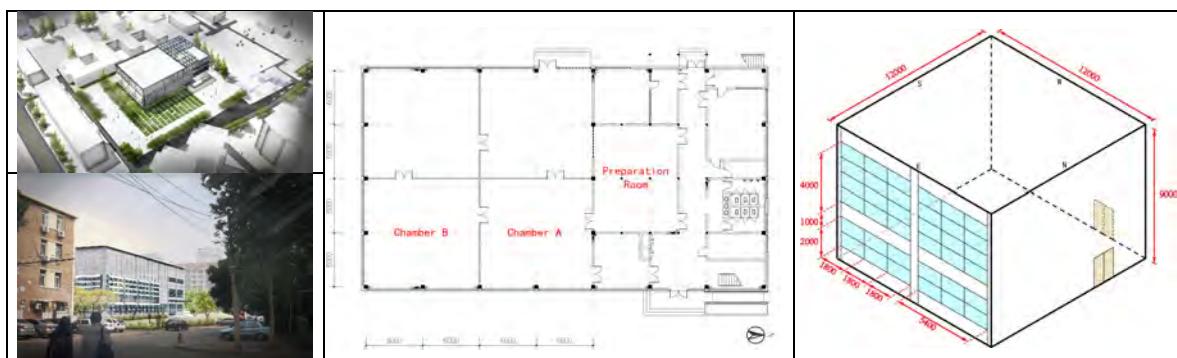


Fig.1 Environment and sizes of space and windows of the CL

Table 1 Figures of subjects

Season	Number	Age	Height(cm)	Weight(kg)	Male : Female
Summer	32	22.5±4.5	173.2±9.4	60.4±15.3	16:16
Winter	32	23.5±3.5	175.6±11.8	63.1±16.5	16:16

### **Experimental conditions**

All the experiments were conducted with the combination of natural lighting and artificial lighting, being controlled at 500 lux. There were three window form categories: window-to-wall ratio (WWR), sill height (SH) and horizontal continuity (HC), containing six different conditions totally, as shown in Table 2 and Table 3. Restricted by existing conditions, there

were three temperature levels in the experiments during summer: 25°C, 27°C, 29°C; and the other three temperature levels in the experiments during winter: 18°C, 20°C, 22°C.

Table 2 Six window form conditions

W1: 20%, 1m	W2: 40%, continuous	W3: 60%
W4: 20%, 4m	W5: 40%, less continuous	W6: 40%, least continuous

Table 3 Three window form categories

Num Categories \	W1	W2	W3	W4	W5	W6
WWR	✓	✓	✓			
SH	✓				✓	
HC		✓			✓	✓

### Measurement

Table 4 Instruments and measuring points during experiments

	1.Onset UX100-003	2.TES-1341	3.HQZY-1
Measuring points in CL		4.TES-1336A	5.HS5671A
		6.AZ77535	

Table 4 shows the instruments used for measuring the different figures of environment in the experiments: 1. air temperature(Ta) and relative humidity (Hum); 2.air velocity (Av); 3. black globe temperature (Tb); 4. indoor illumination; 5. environment noise; 6. concentration of Carbon Dioxide. Ta and Hum were measured at 0.1 m, 0.6 m and 1.1 m high. The subjects, wearing standard clothing ensembles, evaluated thermal comfort under each window form conditions and at the temperature levels (36 times totally). And then they voted for their comfort according ASHRAE's 7-point thermal sensation scale (Table 5).

Table 5 7-point ASHRAE thermal sensation scale

-3	-2	-1	0	1	2	3
Clod	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

## Experimental procedure

All the experiments were conducted in sunny afternoons to avoid direct sunlight, from July 25<sup>th</sup>, 2016 to July 27<sup>th</sup>, 2016 and from January 7<sup>th</sup>, 2017 to January 9<sup>th</sup>, 2017.

Before beginning, there were twenty 20 minutes for the subjects to gather in the laboratory, after which they were required to fill out the clothing questionnaire and to adapt to the temperature for 35 minutes in the preparation room. Everyone had five minutes to accomplish the questionnaire after enough adaptation to the environment with each window form for 25 minutes, during which the environment parameters were measured continuously. After that, five minutes were left for changing window form performance each time by adjusting the curtains, while all the subjects were required to move to the preparation room, prevented from seeing the changing process. They would return to their original seats in the chamber five minutes later after the changing had been completed. During the whole process of the 280 minutes for each experiment, indoor air temperature was kept constant (Fig.2).

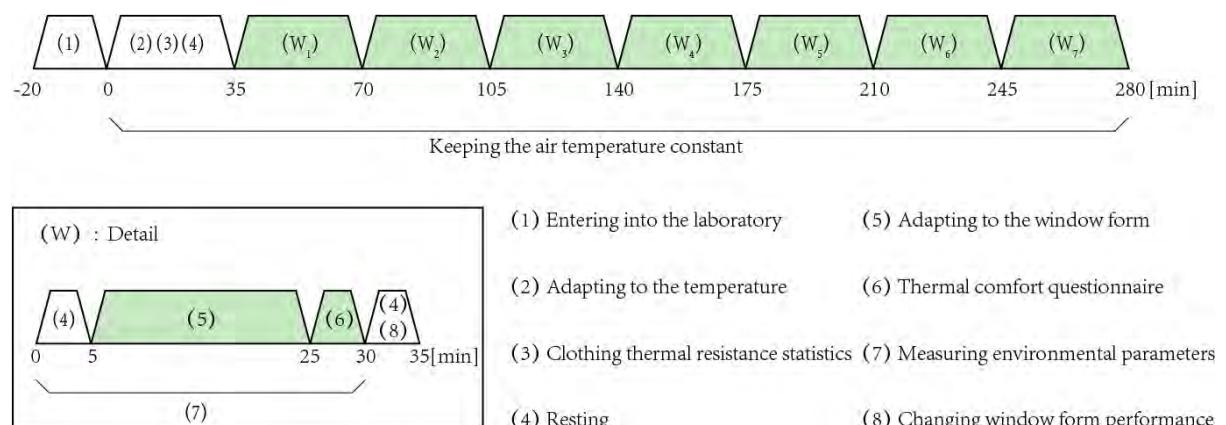


Fig.2 Experimental procedure

## 3. Results and discussion

### 3.1 Indoor climate

Table 6 shows the results of indoor climate measurement and control. Both the concentration of Carbon Dioxide and the noise reached the specifications of experiments in the two seasons. The mean clothing insulation measured was  $0.52 \pm 0.07$  clo during summer and  $0.99 \pm 0.27$  clo during winter.

Table 6 Indoor climate

Design temperature (°C)	Operative temperature (°C)	Hum (%)	Av (m/s)	Illumination (lux)
25	$25.2 \pm 0.18$	$58.3 \pm 0.95$	$0.009 \pm 0.05$	$504.2 \pm 20.9$
27	$27.1 \pm 0.20$	$63.2 \pm 3.20$	$0.010 \pm 0.02$	$507.1 \pm 32.4$
29	$29.1 \pm 0.19$	$59.8 \pm 3.20$	$0.001 \pm 0.01$	$497.6 \pm 18.4$
18	$18.3 \pm 0.13$	$30.1 \pm 0.35$	$0.006 \pm 0.02$	$505.4 \pm 18.6$
20	$20.2 \pm 0.16$	$28.9 \pm 0.20$	$0.005 \pm 0.02$	$516.1 \pm 39.1$
22	$22.3 \pm 0.12$	$21.4 \pm 0.32$	$0.006 \pm 0.02$	$498.3 \pm 15.9$

## *Thermal sensation on the questionnaire*

### *Comparison of window-to-wall ratio in the experiments*

Fig. 3, Table 7 and Table 8 show the results of WWR in the experiments. The slope presents the subjects' sensitivity to operative temperature variations. During summer, the slope of W1 was  $0.5173/^\circ\text{C}$ , while that of W2 and W3 were  $0.4311/^\circ\text{C}$  and  $0.3546/^\circ\text{C}$  respectively. During winter, the slope of W1 was  $0.2492/^\circ\text{C}$ , while that of W2 and W3 were  $0.3871/^\circ\text{C}$  and  $0.3613/^\circ\text{C}$  respectively. We found that people at 20% WWR are more sensitive in summer and less sensitive in winter than at 40% WWR and 60% WWR.

The neutral temperature and acceptable boundary temperature were derived by solving the equations of mean sensation vote of  $0 \pm 0.5$ . During summer, the subjects in W3 had the highest neutral temperature ( $T_n$ ) at  $26.7^\circ\text{C}$  (equal to that in W2) and upper acceptable boundary ( $T_{abu}$ ), and in W1 the lowest  $T_n$  at  $26.2^\circ\text{C}$  and  $T_{abu}$ . During winter, the subjects had the lowest  $T_n$  at  $22.4^\circ\text{C}$  but the highest lower acceptable boundary ( $T_{abl}$ ) in W2 (similar to that in W3), and the highest  $T_n$  about  $22.9^\circ\text{C}$  but the lowest  $T_{abl}$  in W1. The results showed that people at 20% WWR prefer a slightly cooler environment in summer with smaller acceptable range, and a slightly warmer environment in winter with greater acceptable range than at 40% WWR and 60% WWR.

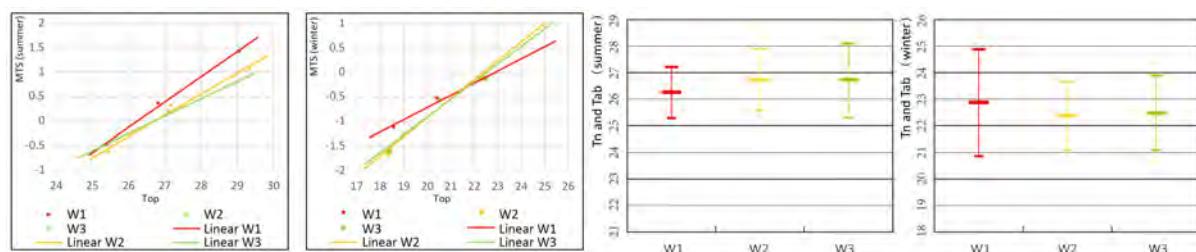


Fig. 3 The result of thermal sensation vote of WWRs

Table 7 Linear fitting of WWRs

	MTS-T <sub>op</sub>	Linear fitting formula	R <sup>2</sup> value
Summer	W1	MTS = $0.5173 T_{op} - 13.577$	0.9976
	W2	MTS = $0.4311 T_{op} - 11.522$	0.9818
	W3	MTS = $0.3546 T_{op} - 9.4754$	0.9953
Winter	W1	MTS = $0.2492 T_{op} - 5.7007$	0.9981
	W2	MTS = $0.3871 T_{op} - 8.6641$	0.9647
	W3	MTS = $0.3613 T_{op} - 8.1383$	0.9594

Table 8 Neutral temperature and acceptable boundary temperature of WWRs

°C	Summer			Winter		
	W1	W2	W3	W1	W2	W3
Neutral temperature	26.2	26.7	26.7	22.9	22.4	22.5
Acceptable boundary (MTS=-0.5)	25.3	25.6	25.3	20.9	21.1	21.1
Acceptable boundary (MTS= 0.5)	27.2	27.9	28.1	24.9	23.7	23.9
Acceptable range (MTS $\in$ [-0.5, 0.5])	1.9	2.3	2.8	4.0	2.6	2.8

### *Comparison of sill height in the experiments*

Fig.4, Table 9 and Table 10 show the results of SH in the experiments. The slope of W4 at  $0.3736/^\circ\text{C}$  in summer was lower than that of W1 by  $0.1437/^\circ\text{C}$ , while  $0.3287/^\circ\text{C}$  in winter higher than that of W1 by  $0.0795/^\circ\text{C}$ .

The neutral temperature of W4 was 25.9°C in summer, 0.4°C lower than that of W1 and 22.4°C in winter, 0.5°C lower than that of W1. W1 and W4 had the same Tabu in summer and the same Tabl in winter.

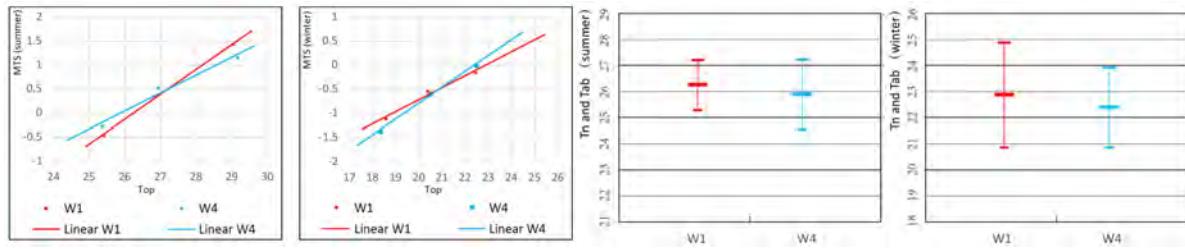


Fig. 4 The result of thermal sensation vote of SHs

Table 9 Linear fitting of SHs

	MTS-T <sub>op</sub>	Linear fitting formula	R <sup>2</sup> value
Summer	W1	MTS = 0.5173 T <sub>op</sub> - 13.577	0.9976
	W4	MTS = 0.3736 T <sub>op</sub> - 9.6736	0.9775
Winter	W1	MTS = 0.2492 T <sub>op</sub> - 5.7007	0.9781
	W4	MTS = 0.3287 T <sub>op</sub> - 7.3611	0.9969

Table 10 Neutral temperature and acceptable boundary temperature of SHs

°C	Summer		Winter	
	W1	W4	W1	W4
Neutral temperature	26.3	25.9	22.9	22.4
Acceptable boundary (MTS=-0.5)	25.3	24.6	20.9	20.9
Acceptable boundary (MTS= 0.5)	27.2	27.2	24.9	23.9
Acceptable range (MTS $\in$ [-0.5, 0.5])	1.9	2.6	4	3

#### Comparison of horizontal continuity in the experiments

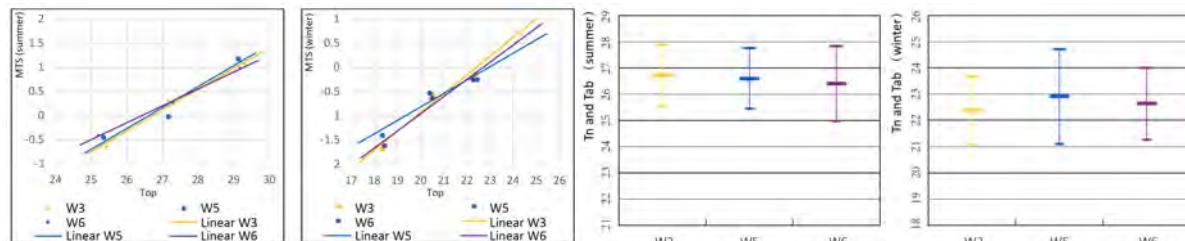


Fig. 5 The results of thermal sensation vote of HCs

Table 11 Linear fitting of HCs

	MTS-T <sub>op</sub>	Linear fitting formula	R <sup>2</sup> value
Summer	W2	MTS = 0.4311 T <sub>op</sub> - 11.522	0.9818
	W5	MTS = 0.4328 T <sub>op</sub> - 11.515	0.9398
	W6	MTS = 0.3499 T <sub>op</sub> - 9.2409	0.9946
Winter	W2	MTS = 0.3871 T <sub>op</sub> - 8.6641	0.9647
	W5	MTS = 0.2774 T <sub>op</sub> - 6.3559	0.9095
	W6	MTS = 0.3544 T <sub>op</sub> - 8.0365	0.9584

Fig.5, Table 11 and Table 12 show the results of HC in the experiments. During summer, the subjects in W6 were a little less sensitive than in W2 and W5 by about 0.08/° C. During winter, the subjects in W5 were the least sensitive among the three HCs.

The neutral temperature of the three HC conditions was almost the same in summer with a maximum difference of  $0.3^{\circ}\text{C}$  with similar Tabu. In winter, W2 had the lowest neutral temperature at  $22.4^{\circ}\text{C}$ , while W5 had the highest at  $22.9^{\circ}\text{C}$ , and their Tabl were almost the same. As for the aspect of neutrality, continuous window form had very small advantage over the other two conditions both in summer and in winter.

Table 12 Neutral temperature and acceptable boundary temperature of HCs

°C	Summer			Winter		
	W2	W5	W6	W2	W5	W6
Neutral temperature	26.7	26.6	26.4	22.4	22.9	22.7
Acceptable boundary (MTS=-0.5)	25.6	25.5	25.0	21.1	21.1	21.3
Acceptable boundary (MTS= 0.5)	27.9	27.8	27.8	23.7	24.7	24.1
Acceptable range (MTS $\in$ [-0.5, 0.5])	2.3	2.3	2.8	2.6	3.6	2.8

### Significance test

Table 13 is the multivariate analysis of variance of the three different window form categories. Operative temperature has significant impact on thermal sensation ( $P<0.001$ ). WWR also had significant impact on thermal sensation depending on the results in summer ( $P<0.05$ ), though it didn't show significant impact in winter ( $P>0.05$ ). The impact of SH and HC on thermal sensation did not reach a significant level in the two seasons ( $P>0.05$ ).

Table 13 Multivariate analysis of variance

Categories	Season	Source	Sum Of Squares	diff	Mean square	F	P
WWR	Summer	WWR	4.719	2	2.360	3.823	.023*
		Top	123.391	2	61.696	99.959	.000*
	Winter	WWR	1.908	2	.954	1.523	.220
		Top	93.261	2	46.631	74.423	.000*
SH	Summer	SH	.045	1	.045	.077	.782
		Top	83.373	2	41.687	70.747	.000*
	Winter	SH	1.908	1	.123	.202	.654
		Top	93.261	2	23.152	38.117	.000*
HC	Summer	HC	.064	2	.32	.048	.953
		Top	83.373	2	56.359	85.065	.000*
	Winter	HC	.608	2	.304	.505	.604
		Top	98.490	2	49.245	81.843	.000*

### Conclusion

The conclusions are as follows:

- Operative temperature has significant impact on thermal sensation.
- The neutral operative temperature of summer and of winter is different. It is between  $25.9^{\circ}\text{C}$  and  $26.7^{\circ}\text{C}$  in summer, and between  $22.4^{\circ}\text{C}$  and  $22.9^{\circ}\text{C}$  in winter, lower than that of summer by about  $4^{\circ}\text{C}$ .
- In most cases, people in summer are more sensitive to indoor operative temperature variations than in winter.
- The present study suggests that window-to-wall ratio might have significant impact on thermal comfort, especially in summer, while sill height and horizontal continuity might have little impact on thermal comfort. The conclusions still need further study.

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## References

- Boyce, P. R., Hunter, C., & Howlett, O. (2003). The benefits of daylight through windows. Troy, NY: Lighting Research Centre.
- Brager G S, de Dear R J. (1998). Thermal adaptation in the built environment: a literature review [ J]. Energy and Buildings, 27(1), 83-9.
- Bruder, W. (2011). Light defines the journey of our lives. *Daylight & Architecture*, 15 (Spring), 58-70.
- Butler, D. L., & Biner, P. M. (1989). Effects of setting on window preferences and factors associated with those preferences. *Environment and Behaviour*, 21(1), 17-31.
- Butler, D. L., & Biner, P. M. (1990). A preliminary study of skylight preferences. *Environment and Behaviour*, 22(1), 119-140.
- Cohen, S., Kessler, R. C., & Gordon, L. U. (1997). Strategies for measuring stress in studies of psychiatric and physical disorders. In S. Cohen, R. C. Kessler & L. U. Gordon (Eds.), *Measuring stress: A guide for health and social scientists* (pp. 3-26). New York: Oxford University Press.
- Collins, B. L. (1976). Review of the psychological reaction to windows. *Lighting Research and Technology*, 8(2), 80- 88.
- Farley, K. M. J., & Veitch, J. A. (2001). A room with a view: A review of the effects of windows on work and well-being. (IRC-RR-136). Ottawa, ON: NRC Institute for Research in Construction.
- Hartig, T., Mang, M., & Evans, G. W. (1991). Restorative effects of natural environment experiences. *Environment and Behaviour*, 23, 3-26.
- Hawkes, D. (2011). Imagining light: The measurable and the unmeasurable of daylight design. *Daylight & Architecture*, 15(Spring), 27-38.
- Humphreys M A, Nicol J F. (1998). Understanding the adaptive approach to thermal comfort[G]. *ASHRAE Trans*, 104(1), 91- 1004.
- Kaplan, R., & Kaplan, S. (Eds.). (1989). *The experience of nature: A psychological perspective*. New York, NY: Cambridge University Press.
- Kaplan, R. (2001). The nature of the view from home: Psychological benefits. *Environment & Behaviour*, 33(4), 507- 542.
- Kaye, S. M., & Murray, M. A. (1982). Evaluations of an architectural space as a function of variations in furniture arrangement, furniture density, and windows. *Human Factors*, 24(5), 609-618.
- Keighley, E. C. (1973b). Visual requirements and reduced fenestration in offices: a study of window shape. *Building Science*, 8, 311-320.
- Stamps, A. E., III. (2004). Mystery, complexity, legibility and coherence: A meta-analysis. *Journal of Environmental Psychology*, 24(1), 1-16.
- Stamps, A. E., III. (2007). Mystery of environmental mystery. *Environment and Behaviour*, 39(2), 165-197.
- Stamps, A. E., III, & Krishnan, V. V. (2006). Spaciousness and boundary roughness. *Environment and Behaviour*, 38(6), 841-872.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## The impact of environmental color on summer thermal comfort in the cold climate zone of China

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**Abstract:** This study assessed the effect of environmental color on thermal comfort through a series of experiment in a climate chamber. Twenty one experiments were conducted in seven environmental chambers with different color of walls (white, extreme red, light red, extreme yellow, light yellow, extreme blue and light blue). The size of the chambers were kept the same (6m\*6m\*5m) and 32 persons (16 males and 16 females) were tested. In each environmental chamber, the subjects were exposed to three ambient temperature levels (25°C, 27°C or 29°C). A questionnaire on thermal comfort was distributed and accomplished after the subjects had read or studied for 1/2 hour in each experiment. And the neutral point of temperature and comfortable temperature range were predicted according to the subjects' mean thermal sensation vote (MTSV). The results indicate that the subjects preferred a slightly higher neutral point of temperature and a wider comfortable temperature range in extreme blue chamber than in extreme red or extreme yellow ones. While for the white, light red, light yellow and extreme blue environment, the neutral point of temperature and comfortable temperature range were very close. In addition, in light red and light yellow chambers, the subjects could endure a higher comfortable temperature limit than in extreme red and extreme yellow chambers. Lastly, implications of the findings and suggestions for environmental design and energy savings are discussed.

**Keywords:** Color, thermal comfort, energy saving, hue-heat-hypothesis, value

### Introduction

As one of the main challenges towards a more sustainable future, reducing energy consumption in buildings has been taken seriously over recent years. Researchers focused on considerable numbers of areas such as retrofit strategies and “smart technologies”, behavior change programmes and so on. Also, extensive researches have been carried out on whether some athermal factors can affect a person's thermal sensation or thermal comfort. In this paper, we researched a different approach towards reducing energy consumption based on the color of surroundings, which is also closely related to architecture design. An affirmative answer could lead to interesting energy saving consequences. Compared with extreme red, we may paint or furnish a room with extreme blue, light blue or even light red in summer, which can decrease the temperature needed for comfort and make people feel delighted and satisfied.

A few earlier investigations studied the thermal effect of colors on man's preferred ambient temperature or judgment of room temperature. Some found effects in line with hue-heat-hypothesis: Itten and Clark found that subjects feel colder in rooms with blue/blue-green walls. G.M. Huebner found that the color of light can almost affect thermal sensation, and subjects feel significantly warmer under the light of 2700 K than 6500 K. However, others did not observe any reliable effect of environment color on the judgment

of room temperature or comfort. Two studies exposed subjects to differently colored rooms, and the temperature estimated by the subjects did not differ significantly between settings. Bennett and Rey found that wearing colored googles did not have any effect on the judgment of thermal temperature. Fanger found that subjects preferred a slightly lower ( $0.4^{\circ}\text{C}$ ) ambient temperature in the extreme red light than in the extreme blue light. Even if the effect was so small to have any practical significance, we could not deny that color light might influence thermal comfort. The different outcome varied from temperature estimates and comfort ratings, indicating that people can possibly dissociate between comfort feeling and temperature estimates, which can be supported by the notion that self-reported thermal sensation, thermal preference, and thermal comfort are qualitatively different.

While people always prefer light color in rooms. Light colors are widely used in architecture design. However, few studies discussed whether colors with different value and chroma are related with thermal comfort. Some research on color psychology and performance asserted the effect of value and chroma. Stone set a dark red and light blue offices to test whether color will affect officers' performance. Prabu Wardono decorated restaurant with dark yellow, light yellow, dark green and light green to discuss psychological effect on having meals.

To summarize, existing research is somewhat ambiguous regarding relationship between color and thermal comfort. Some conditions seem to be associated with the absence of effect of color on thermal perception: judging a room's temperature, performing an engaging task and so on. Previous studied also suffered from methodological issues, such as insufficient control for varying temperature levels and other factors that can impact on thermal comfort, using googles to change the color of environment. Finally, since the effect of hue-heat-hypothesis was uncertain, few studies noticed about the value and chroma, even though light colors are widely used in buildings compared with dark colors.

## **Experimental Method**

### ***Subjects***

Male (n =16) and female (n=16) students volunteered for this study. Most of the students were between the age of 18 and 25 years old, 2 were 28, and 1 was 30. They were healthy and had been living in Tianjin for more than three years. In the experiments, they all kept sedentary activity, like reading or studying.

### ***Experimental set-up and equipment***

Twenty-one experiments were conducted in seven environmental chambers with different colors of wall (white, extreme red, light red, extreme yellow, light yellow, extreme blue and light blue). In each environmental chamber, the subjects were exposed to three ambient temperature levels ( $25^{\circ}\text{C}$ ,  $27^{\circ}\text{C}$  or  $29^{\circ}\text{C}$ ).

The color of walls was chosen according to Munsell book of color, 1970. The three extreme colors (5R4/14, 5Y8/12 and 5B5/8) were the purest in red, yellow and blue hues. As a contrast on value and chroma, we also chose light red (5R8/4), light yellow (5Y9/4) and light blue (5B9/4). In addition, we use white (N9) as neutral color. The temperature levels were chosen in terms of GB 50736 and ISO7730.

The test was carried out in enclosed climate chamber, in which temperature, humidity, and air velocity could be controlled. All the chambers were kept with the same size (6m\*6m\*5m). To prevent glare from reflecting from plaster walls, the walls around were

covered with 600D PVC cloth, which was colored with seven colors chosen. Four chairs and desks were positioned in the center of each room for the participants.

Ambient temperature and relative humidity were measured at three heights (1.1 m, 0.6 m, and 0.1 m), using three Hobo sensors (OnsetHOBO U12-012) that were calibrated prior to use and had a sampling rate of 1-minute. In order to facilitate comparison, it was decided to use the same activity (sedentary activity), clothing (0.6 clo standard clothing), air velocity (< 0.1 m /s), relative humidity (50-70%), mean radiant temperature equal to air temperature, etc. The relative humidity was 20-30%.



Figure 1 Photograph of experimental set-up

### **Procedure**

The subjects reported in good time prior to the commencement of the experiment. Before starting the test, it was ascertained that the subjects had had sufficient sleep and normal meals, had not have a cold or a fever, and had not consumed alcohol during the previous 24 h. Before they entered the chambers, they should keep seated and rest in the preparation room for more than 30 min.

Each four subjects entered a chamber. During the exposure, the subjects were kept occupied by reading, and were prohibited from eating, drinking or smoking while the test was in progress. The subjects sat in the centre of the chamber in chair with seat and back of plastic strips, which had only negligible influence on the persons' heat loss to the environment. A questionnaire on thermal comfort was distributed and accomplished after the subjects had been reading or studying for 1/2 hour in each experiment. Then they entered another chamber with different color or temperature, repeating the procedure above. Each subject should experience all of the 21 kinds of chambers.

During the experiment, air temperature was kept at 0.5°C up or below presupposed temperature levels by adjusting air-conditioning according to the indicating number of HOBOs at the height of 1.1 m.

## Survey

The subjects needed to fill in thermal comfort survey (Table 1) after reading or studying in each experiment for more than 30 min. The questions in the survey correspond to the ASHRAE standard scales for thermal comfort. This produced nearly 1500 data responses describing their perceptions. And the neutral point of temperature and comfortable temperature range were predicted according to the subjects' mean thermal sensation vote (mTSV).

Table 2 Thermal sensation.

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

## Result

From the temperature range from 25°C to 29 °C, the percentage of thermal sensation vote is given in Figure 2. The proportions of TSV in different color of rooms have some similarities. With the temperature increasing, the number of the subjects who felt warm or hot (TSV > 0) is growing whatever color of wall in the chamber is. At 29 °C, the subjects who chose "+2" or "+3" increase obviously; at 27°C, in all of the seven kinds of colored space the proportions of "TSV < 0, TSV=0 or TSV>0" are very close (difference being below 15%).

Meanwhile, at different level of the temperature, the proportions of TSV between different color also have difference. At 25°C, blue room and white room have the highest proportion of "cool" or "cold"; at 29°C, when studying in red, yellow, light red and light yellow chamber respectively, more subjects tend to select the "+3" than other conditions, moreover in light red chamber and light yellow chamber , it has the highest proportion of "neutral ", whose value is around 50%.

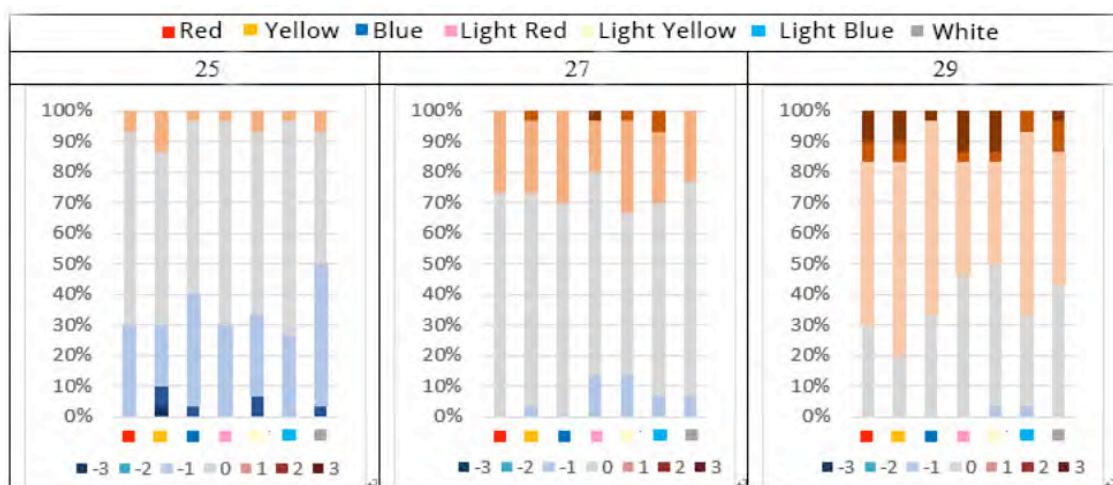
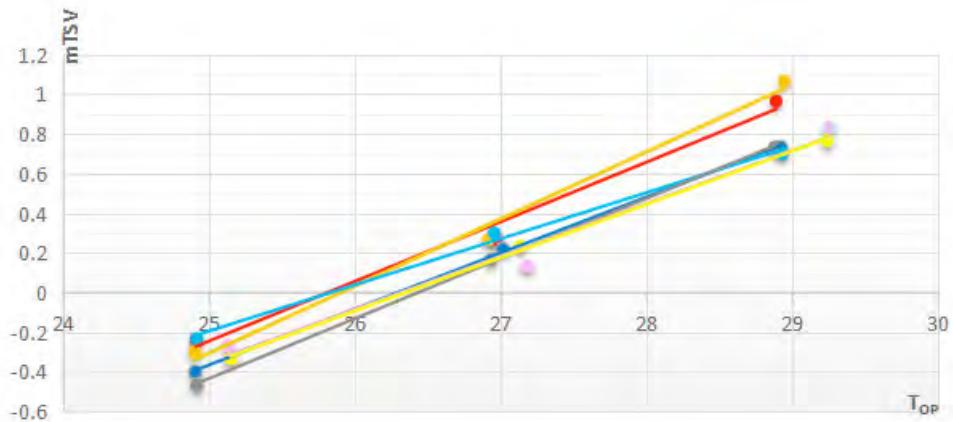


Figure 2 Percentage of Thermal Sensation Vote

Figure 3 shows the mean thermal sensation vote (mTSV) of all of the seven colors. The mTSV of each color is calculated from 30 data. And regression equations are given in Figure 2. The graph indicates that the subjects in extreme red chamber and extreme yellow chamber almost feel hotter than in other colored chambers, ranging from 25°C to 29°C. The graphs of extreme blue, light red, light yellow and white are very similar.

To sum up, color has influence on TSV or mTSV, and the impact differs with different temperature. Hue, value and chroma can affect TSV or mTSV.



■ Red ■ Yellow ■ Blue ■ Light Red ■ Light Yellow ■ Light Blue ■ White

Color	Regression equation	R <sup>2</sup>
Red (5R4/14)	y = 0.3007x - 7.7622	0.9865
Light red (5R8/4)	y = 0.2672x - 7.032	0.9766
Yellow (5Y8/12)	y = 0.3384x - 8.7661	0.9907
Light yellow (5Y9/4)	y = 0.2688x - 7.0822	0.9988
Blue (5B5/8)	y = 0.2823x - 7.4235	0.9994
Light blue (5B9/4)	y = 0.2327x - 6.0125	0.9947
White (N9)	y = 0.3028x - 8.0034	0.9995

Figure 3 Regression Equation of Seven Colors

## Discussion

### The impact of hue on thermal comfort

Figure 4 shows the neutral point of temperature and comfortable temperature range ( $mTSV=[-0.5,0.5]$ ) of extreme red, yellow, blue and white, according to which the impact of hue on thermal comfort can be discussed ( $p<0.05$ ).

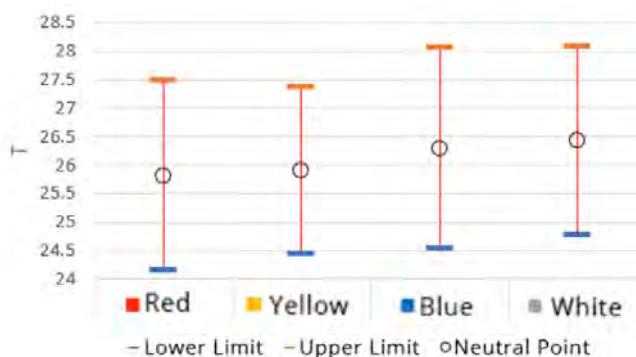


Figure 4 Neutral point of temperature and comfortable temperature range

The results indicate that the subjects preferred a slightly higher neutral point of temperature in extreme blue or white chambers than in extreme red or extreme yellow chambers. The neutral point of extreme blue is 0.49°C higher than red, and 0.4°C higher

than yellow; the neutral point of white is 0.62°C higher than red, and 0.53°C higher than yellow.

In addition, in extreme blue chambers, the subjects could endure a higher comfortable temperature limit and a wider comfortable temperature range than in extreme red or yellow chamber. The comfortable temperature limit in extreme blue or white chamber is 0.6-0.7°C higher than that in extreme red or yellow chamber. The comfortable temperature range is 0.21°C wider in extreme blue room than that in extreme red one, 0.59°C wider in extreme blue room than in extreme yellow one.

However, the neutral point of temperature and comfortable temperature limit in extreme blue and white, extreme red and extreme yellow chambers are very close.

To sum up, a blue-colored or white-colored room may have more energy-saving potential than a red-colored or yellow-colored one in summer theoretically, owing to a higher neutral point and temperature limit. However, the difference is very slight (<1°C) to make sure that hue really has practical significance.

### ***The impact of value and chroma on thermal comfort***

Figure 5 shows neutral point of temperature and comfortable temperature range ( $mTSV = [-0.5, 0.5]$ ) of extreme red and light red, extreme yellow and light yellow, extreme blue and light blue, according to which the impact of value and chroma on thermal comfort can be discussed.

The results showed that the subjects preferred a slightly higher neutral point of temperature in light red chamber or light yellow chamber than in extreme red or extreme yellow chamber. The neutral point of extreme red is 0.5°C lower than light red; the neutral point of extreme yellow is 0.44°C lower than light yellow. However, the neutral point of extreme blue is 0.47°C higher than light blue.

Moreover, in light red chamber and light yellow chamber, comfortable temperature limit is much higher than that in extreme red and extreme yellow ones; comfortable temperature range is wider, too. The limit of light red is 0.71°C higher than extreme red, and the range is 0.42°C wider. The limit of light yellow is 0.83°C higher than extreme red, and the range is 0.77°C wider. Besides, in spite of a close comfortable limit, the comfortable temperature range is 0.76°C wider in light blue than extreme blue.

To sum up, a light red-colored or yellow-colored chamber may have more energy-saving potential than an extreme red-colored or yellow-colored chamber in summer theoretically. Their comfortable temperature limits and neutral points of temperature are higher. However, the difference is very slight (<1°C) to make sure that value and chroma really have practical significance for red and yellow. Similarly, we can't be convinced of an apparent effect on thermal comfort, as blue color of a room turns light.

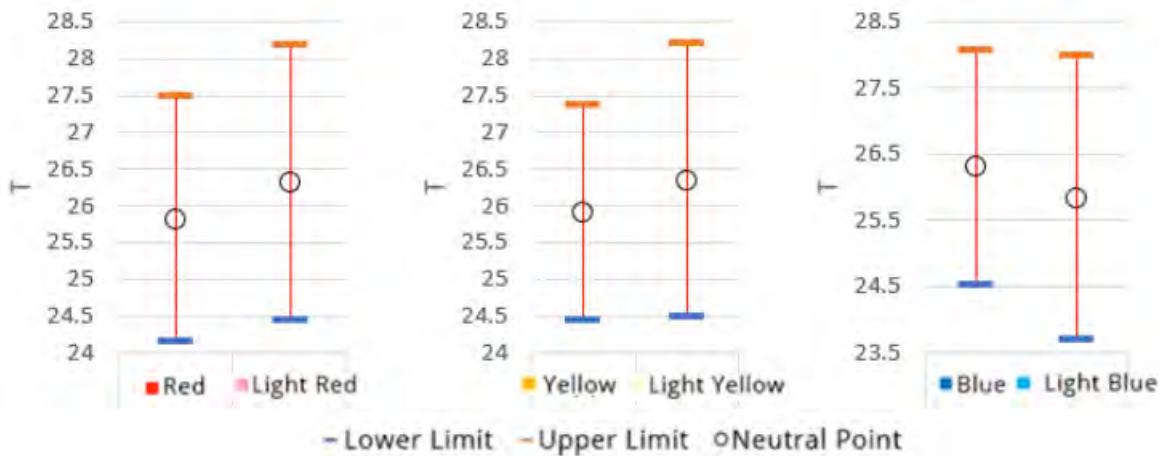


Figure 5 neutral point of temperature and comfortable temperature range

## Conclusions

The results indicated that “warm” or “cold” color, “extreme” or “light” color can affect a person’s thermal sensation or thermal comfort theoretically, since neutral point of temperature and comfortable temperature range differed when the subjects were in the chambers with different hue, value or chroma. However, the difference is very slight ( $<1^{\circ}\text{C}$ ) to make sure that hue really have practical significance.

Despite the result shows that color may have little actual energy saving potential, we can improve the experimental design from limitations of the studies. For instance, the study tested only a narrow temperature range and sedentary activities of subjects. Further research needs to define the magnitude of the effect, determine the exact range of ambient temperatures in which color impacts on thermal comfort, in particular high temperatures and variations of subjects’ activity, too. What’s more, the sample was limited to the age range tested; it might give different comfort preferences varying with age. Furthermore, we should make sure that differentially colored space does not impact on mood or performance negatively. Finally, when we discuss which color we should design in a space, we must measure positive or negative effect comprehensively on energy saving, economy, architectural experience, physical and mental health of people and so on. It is such a complicated question that we need more further studies and researches.

## Acknowledgements

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## References

- C.A. Bennett et al (1972), What’s so hot about red? *Hum. Factors* 14 (2) p149–154.
- D.M. Pedersen et al (1978), Effects of room hue on ratings of self: other and environment, *Percept. Mot. Skills* 46 p403–410.
- G. Brager et al (1993), A comparison of methods for assessing thermal sensation and acceptability in the field, in: Proceedings of Thermal Comfort: Past, Present and Future, *Center for the Built Environment*, UC Berkeley, Retrieved from: <http://escholarship.org/uc/item/5n94s9hz> (accessed 16.06.15).
- J. Itten (1961) , *Die Kunst der Farbe*, O. Maier, Ravensburg.
- L. Clark (1975) , *The Ancient Art of Color Therapy*, Diving-Adair, Old Greenwich, CT,1975.

Prabu Wardono et al (2010). Effects of Restaurant Interior Elements on Social Dining Behaviour, *Asian Journal of Environment-Behaviour Studies*.

Stone, N. J., & English, A. J. (1998). Task Type, Posters, and Workspace Color on Mood, Satisfaction, and Performance. [doi:10.1006/jevp.1998.0084]. *Journal of Environmental Psychology*, 18(2), 175-185

T.C. Greene et al (1980, Additional considerations concerning the effects of warm and cool colours on energy conservation, *Ergonomics* 23 (10) p949–954.



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*Design to Thrive*

## Indoor Thermal Comfort Assessment of Naturally Ventilated Retail Food Establishment in Singapore

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**Abstract:** Thermal comfort is one of the issues in naturally ventilated building. In order to assess the thermal comfort in future development of retail food establishment in Singapore, thermal comfort survey was conducted in several existing eating places. The survey comprised of objective measurement of indoor environmental parameters as well as subjective measurement using questionnaire on the patrons before they started eating. The measurement data were analysed statistically using correlation and regression to develop the thermal comfort model or Predicted Mean Vote (PMV) equation. Air temperature, wind speed and mean radiant temperature (MRT) are found to significantly affect the PMV. Although significant, the MRT has very little effect on the PMV and therefore, MRT is not included in the thermal comfort model. The wind speed required to achieve thermal comfort is very low, which might be due to the low thermal comfort expectation and the short duration of stay by the respondents. In the calculation for the thermal comfort assessment, air temperature is assumed to be 2°C higher from the average 30-year air temperature data to accommodate the heat built-up from the food stalls, while still within the interquartile range of the measured indoor air temperature.

**Keywords:** indoor thermal comfort, naturally ventilated, food establishment, Singapore

### Introduction

Singapore is under tropical rainforest climate zone, experiencing hot and humid weather with extensive sunshine and excessive rainfall. Naturally ventilated buildings in tropical climate face the issue of thermal comfort and/or wind driven rain. In order to minimise energy consumption through the use of natural ventilation while ensuring sustainable building performance by minimising the associated issues, Building and Construction Authority (BCA) commissioned a research project to look into the ventilation, the thermal comfort, and the wind driven rain aspects of naturally ventilated non-residential buildings in Singapore. This paper focuses on developing the thermal comfort model, analysis and validation, as well as recommending the assessment criteria for future development of naturally ventilated retail food establishment in Singapore.

Thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment (ASHRAE, 1992). Thermal comfort perception is affected by the psychology and physiology of the occupant as well as the design of the building and the climatology.

On the other hand, naturally ventilated buildings depend on climatic and geographical characteristic where it is located. Inevitably, its indoor condition is governed by external environmental factors such as wind, humidity, air temperature and solar radiation. Its climate

dependence makes it relatively more unpredictable in estimating and securing a thermally comfortable condition. In tropical climate condition, buildings are found to be uncomfortably hot and humid at certain times, and higher velocity of wind flow over the human body is required to increase the efficiency of sweat evaporation (Yeang, 1987).

In Singapore, there are many naturally ventilated retail food establishments with different scales, ranging from individual food outlet to food centre which houses many outlets together. These eating places provide sheltered and hygienic infrastructure as well as cheap and affordable food to the general public.

There is limited research that studies about thermal comfort in retail food establishments in Singapore. The first research study found that the unfavourable conditions found in hawker centres were caused by the combined effects of air temperature, relative humidity and roof thermal insulation, which could be improved by installing fans to increase air movement and using reflective aluminium foil to reduce the roof thermal radiation (Rao et al, 1978). In the following study, it was found that the most effective solution to solve the poor thermal comfort condition was to improve the cross-ventilation by increasing the roof height, and followed by increasing the width of the centre passageway (Wong et al, 2003). The better way to use mechanical ventilation system to improve the thermal condition was to install the exhaust fans in the cooking area and to install the wall fans in the eating area (Wong et al, 2006).

## **Methodology**

### ***Objective and Subjective Measurements***

Data was collected through field survey. The measurement protocol for the field survey followed Class II protocol of thermal comfort field research (Brager et al, 1998). The field survey consisted of two parts, i.e. objective measurement which measured the environmental parameters affecting thermal comfort, as well as subjective measurement which captured the thermal perception of occupants in their actual daily environment. The environmental parameters measured were air temperature, relative humidity, wind speed, and globe temperature to calculate mean radiant temperature at the time of the subjective measurement. The measurement was conducted using handheld equipment of Testo 445 which had a standard globe thermometer (accuracy of  $\pm 0.5^{\circ}\text{C}$ ) and a 3-function probe for simultaneous measurement of air temperature (accuracy of  $\pm 0.3^{\circ}\text{C}$ ), relative humidity (accuracy of  $\pm 2\%$ ), and wind speed (accuracy of  $\pm 0.05 \text{ m/s}$ ). The measurement was near each occupant (respondent) and at around 0.8 – 1 m high from the floor. From each respondent, the clothing and the activity information were noted down as well.

The subjective assessment was formulated into a questionnaire form. Standard form of both seven scale of ASHRAE thermal sensation (Thermal Sensation Vote or TSV) and seven scale of Bedford thermal perception (Thermal Comfort Vote or TCV) are used (Chrenko, 1974; McIntyre, 1980). By using both scales, the consistency of response between thermal sensation (hot to cold) and perception (uncomfortable-comfortable warm or cold) can be further verified.

During the period of the indoor survey, a weather station was installed on the roof of the building to measure the outdoor weather condition. The monitored parameters included ambient temperature, wind speed, and solar radiation.

### ***The Thermal Comfort Survey***

The subjects of the field survey were the patrons before they started eating to ensure the respondents' feedback would not be affected by the food they consumed. The thermal comfort surveys were conducted during lunch and dinner time to cover different parts of the day. The objects of study were four naturally ventilated retail food establishments in Singapore which consisted of different building designs.

Site A is part of a building designed with higher ceiling height from floor; the eating area is equipped with ceiling, wall, and High Volume Low Speed (HVLS) fans; and each cooking stall is connected to the mechanical exhaust system. Most of the eating area is on the eastern and the northern sides of the site which are open for natural ventilation and equipped with louvers as shading. The weather during the survey was in the range from partly cloudy to cloudy on the first day, and bright on the second day. 165 data were collected.

Site B is similar to Site A. The area is also designed with higher ceiling height from floor; the eating area is equipped with wall and HVLS fans; and each cooking stall is connected to the mechanical exhaust system. Part of the eating area is in between the rows of cooking stalls and the other is next to the opening on the southern side. Most of the opening is on the southern side with vertical louvers as shading. There is opening with shaded corridor on the western side as side entrance. The weather during the survey was partly cloudy to cloudy on the first day, and partly cloudy to bright on the second day. 164 data were collected.

Site C is part of a building designed with lower ceiling height from floor and smaller area for each cooking stall; the eating area is equipped with wall fans and jet fans; but there is no mechanical exhaust from each cooking stall. Most of the eating area is in between of rows of cooking stalls. The openings for natural ventilation are on the western and the south-western sides as well as a courtyard in the middle of the site which opens to the sky. The weather during the survey was bright. 115 data were collected.

Site D is a single-storey stand-alone building which has metal roof and lower ceiling height from floor with openings on the east-west sides; the eating area is between the rows of cooking stalls and equipped with wall fans; and there is no exhaust from the cooking stall. The weather during the survey was partly cloudy to bright. 127 data were collected.

## **Result and Discussion**

### ***Field Measurement Data***

The overall thermal comfort surveys collected a total of 571 respondents. Table 1 shows the measured outdoor weather condition during the time of the thermal comfort survey.

Table 2 shows the measured indoor environment condition around the respondents. The average of overall outdoor air temperature was 31.5°C. The median of the overall indoor air temperature was also 31.5°C. The indoor wind speed was measured mostly at the range of 0.44 – 0.84 m/s due to the usage of fans, while mean radiant temperature was at the range of 32.1 – 33.9°C.

Table 1. Summary of the outdoor weather data

	Minimum	Maximum	Mean	Standard Deviation
Temperature (°C)	28.1	35.8	31.5	1.5
Wind Speed (m/s)	0.0	4.6	0.6	0.7
Solar Radiation (W/m <sup>2</sup> )	0.6	923	339	242

Table 2. Summary of the indoor environment measurement around the respondents

	Minimum	Maximum	Median	Interquartile Range
Temperature (°C)	28.7	38.3	31.5	30.5 – 32.6
Wind Speed (m/s)	0.05	2.4	0.6	0.4 – 0.8
Mean Radiant Temperature (°C)	29.7	39.7	32.9	32.1 – 33.9

Thermal acceptability graph was shown in Figure 1. Site C shows the lowest percentage of thermal acceptability which may be due to the weather condition that was bright during the survey. The weighted overall percentages of thermal acceptability for TSV and TCV show that 61% and 77% are acceptable respectively. The higher TCV than TSV shows that the respondents have higher thermal comfort tolerance towards hot sensation.

### ***Thermal Comfort Model Development and Validation***

The thermal comfort survey data was divided into two groups, i.e. one set for model development (457 data) and one set for model validation (114 data). Weighted estimation was made to determine the number of respondents selected from each site and each session for validation purpose.

The computation of the statistical analysis used IBM SPSS® Version 24 software. Multiple regression analysis was employed to find the best combination between the TSV, which would be used as the Predicted Mean Vote (PMV), as dependent variable, and the set of environmental variables as independent variables. The independent variables were the measured indoor air temperature (DBT), relative humidity (RH), mean radiant temperature (MRT) calculated from the globe temperature, wind speed (WIND), clothing level of respondent (CLO) and metabolic rate from the activity of the respondent (MET).

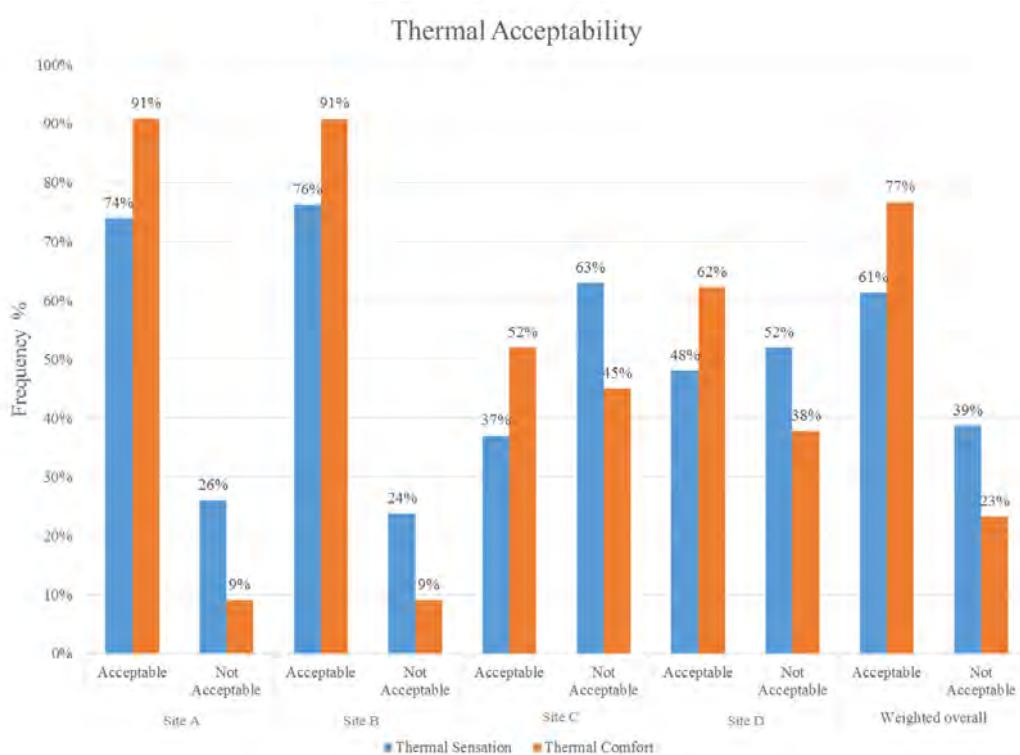


Figure 1. Thermal acceptability

Table 3. Inter-correlation between independent variables and PMV

		PMV	DBT	RH	WIND	TMRT	CLO	MET
TSV	Correlation	1	0.533	-0.391	-0.187	0.252	0.052	-0.050
	Sig.		0.000	0.000	0.000	0.000	0.271	0.283
DBT	Correlation	0.533	1	-0.752	-0.148	0.498	0.213	-0.139
	Sig.	0.000		0.000	0.002	0.000	0.000	0.003
RH	Correlation	-0.391	-0.75	1	0.007	-0.468	-0.215	0.005
	Sig.	0.000	0.000		0.887	0.000	0.000	0.916
WIND	Correlation	-0.187	-0.148	0.007	1	0.172	-0.055	0.062
	Sig.	0.000	0.002	0.887		0.000	0.245	0.184
TMRT	Correlation	0.252	0.498	-0.468	0.172	1	0.193	-0.105
	Sig.	0.000	0.000	0.000	0.000		0.000	0.024
CLO	Correlation	0.052	0.213	-0.215	-0.055	0.193	1	-0.073
	Sig.	0.271	0.000	0.000	0.245	0.000		0.118
MET	Correlation	-0.050	-0.139	0.005	0.062	-0.105	-0.073	1
	Sig.	0.283	0.003	0.916	0.184	0.024	0.118	

Using the data set for model development, Pearson correlations between the dependent variable and independent variables are shown in Table 3. DBT, RH, WIND and TMRT are found to be significant ( $\text{Sig.} < 0.05$  for 2-tailed), but DBT and RH are highly correlated and hence, RH is excluded from the regression analysis. Clothing and metabolic rate are found not significant which might be due to the similar types of clothing in naturally ventilated tropical climate buildings, and due to the similar activity of respondents (i.e. sitting) respectively.

From all combinations in the multiple regression analysis, the combinations that all independent variables combined are significant are shown in Table 4. The effect of TMRT to the equation is very low and hence, combination 2 is considered for the thermal comfort model.

Table 4. Combinations of environmental variables  
Variables in the equation

No	Combinations	DBT	WIND	TMRT	Constant	R <sup>2</sup>	Adjusted R <sup>2</sup>	Residual Mean Square
1	DBT	0.457	-	-	-13.841	0.284	0.283	1.567
2	DBT WIND	0.443	-0.460	-	-13.075	0.296	0.293	1.544
3	DBT WIND TMRT	0.434	-0.482	0.020	-13.436	0.297	0.292	1.547

The equation based on combination 2 can be written as follows:

$$\text{Equation 1. PMV model}$$

$$\text{PMV} = 0.443 \text{ DBT} - 0.460 \text{ WIND} - 13.075$$

To validate the PMV model, data set for model validation is used to compare the measured PMV and the predicted PMV. Figure 2 shows the boxplot of this comparison. Based on median value, the PMV model seems to over predict towards warmer side, but in overall,

75% of the predicted PMV value is within the interquartile range (central tendency) of the measured PMV.

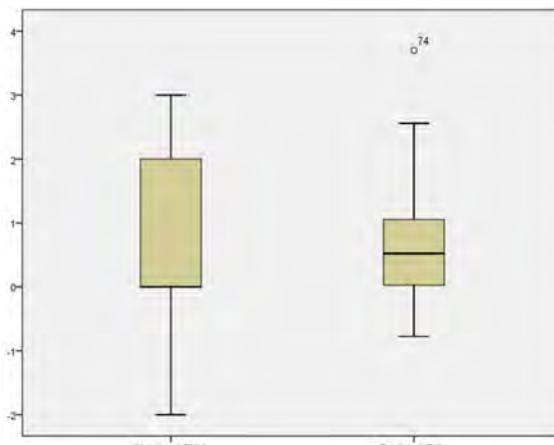


Figure 2. Comparison of measured PMV and predicted PMV for model validation

### **Boundary Condition and Recommendation for Assessment Criteria**

The PMV equation will be used by building designer/consultant to assess the thermal comfort in the future building design. This section discusses how to derive the value for the PMV equation.

The PMV equation has two components, i.e. DBT and WIND. For DBT, 32-year dry bulb temperature from Changi meteorological weather station was analysed, and the most frequently occurred DBT is 30°C. The baseline value of 30°C is raised to 32°C to accommodate the high measured indoor air temperature and to factor in the effect of built-up heat from the cooking stalls.

For WIND, indoor wind speed with or without fans shall be derived from CFD simulation. As a guide, Table 5 show the various wind speed required based on air temperature of 32°C to achieve the various PMV values. The wind speed required to achieve thermal comfort is very low, which might be due to the low thermal comfort expectation and the short duration of stay by the respondents.

Based on this table, PMV 1 as the highest acceptable value is recommended to achieve the lower green building rating, while PMV 0.8 is recommended to achieve the higher green building ration. With PMV 1 and PMV 0.8, the wind speed required is 0.22 m/s and 0.65 m/s respectively, which is within the most frequently measured indoor wind speed during the survey (0.44 – 0.84 m/s).

Table 5. Various wind speed required to achieve various PMV values with DBT 32°C

DBT (°C)	WIND (m/s)	PMV
<b>32</b>	<b>0.22</b>	<b>1.0</b>
32	0.44	0.9
<b>32</b>	<b>0.65</b>	<b>0.8</b>
32	0.87	0.7
32	1.09	0.6
32	1.31	0.5

## Conclusion

The thermal comfort model or PMV equation to assess future retail food establishment development in Singapore is

$$PMV = 0.443 DBT - 0.460 WIND - 13.075$$

Which DBT is indoor air temperature ( $^{\circ}\text{C}$ ) with baseline at  $32^{\circ}\text{C}$  and WIND is indoor wind speed (m/s). The value of WIND shall be derived from the result of indoor ventilation simulation.

By using DBT  $32^{\circ}\text{C}$ , PMV 1 is the highest acceptable value with wind speed required is 0.22m/s and PMV 0.8 is recommended to achieve higher green building rating with wind speed required is 0.65 m/s, which is within the most frequently measured indoor wind speed during the survey (0.44-0.84 m/s).

## Acknowledgments

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## References

- ASHRAE. (1992). *ASHRAE Standard 55-92, Thermal Environment Conditions for Human Occupancy*. Atlanta: Amerian Society of Heating, Refrigerating and Air-conditioning Engineers.
- Brager, G.S., De Dear, R.J. (1998). Thermal Adaptation in the Built Environment: A Literature Review. *Energy and Buildings*, 27, pp. 83-96.
- Chrenko, F.A. (ed.) (1974). *Bedford's Basic Principles of Ventilation and Heating*. London: H.K. Lewis.
- McIntyre, D.A. (1980). *Indoor Climate*. London: Applied Science Publishers.
- Rao, K.R., Ho, H.C. (1978). Thermal Comfort Studies in Hawker Centres in Singapore. *Building Environment*, 13, pp. 161-166.
- Wong, N.H., Song, J., Tan, G.H., Komari, B.T., Cheong, D.K.W. (2003). Natural ventilation and thermal comfort investigation of a hawker center in Singapore. *Building and Environment*, 38, pp. 1335–1343.
- Wong, N.H, Song, J., Istiadji, A.D. (2006). A Study of the effectiveness of mechanical ventilation systems of a hawker centre in Singapore using CFD simulations. *Building and Environment*, 41, pp. 726-733.
- Yeang, K. (1987). *Tropical Urban Regionalism: Building in South-East Asian City*. Singapore: Concept Media.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Effects of the Building Typology on PET Value in Different Local Climate Zones: A Case Study in Beijing, China

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**Abstract:** Under the background of climate change, urban heat stress exacerbates with increasing level of urbanization (Rizwan et al., 2008). Local Climate Zones (LCZ) (Stewart and Oke, 2012) forms a systematic classification scheme that is commonly used nowadays for zoning and classifying the internal structure of urban areas. The world urban database and access portal tools (WUDAPT) (Mills et al., 2015) uses freely available Landsat imagery to create LCZ classification of cities. This study chose samples based on WUDAPT database of Beijing to explore whether different patterns and arrangement of buildings would influence the microclimate in a typical LCZ scale. Physiologically Equivalent Temperature (PET), as the most generally used indicator for thermal environment, will be used to assess the microclimate situation in the study. Result shows that within the same LCZ group, the microclimate situations vary with the building layout typology. To release the urban heat stress in summer, terrace and court typologies are the ideal choices for Beijing. On the contrary, semi-court and pavilion typology will cause extreme heat stress in summer.

**Keywords:** Beijing, LCZ, building layout typology, ENVI-met, PET, WUDAPT,

### Introduction

The fact of climate change and extreme weather creates new demand for the building environment (Luber and McGeehin, 2008, Hallegatte, 2009). The Local Climate Zone (LCZ) system comprises 17 zone types at the local scale, each type contributes differently to the temperature increasing (Stewart and Oke, 2012). Its framework could be used to classify the aimed site into appropriate LCZs, and it could support the city planners, landscape designers, and global climate change investigators to make decisions. Using LCZ as the logical starting point, the World Urban Database and Access Portal Tools (WUDAPT) uses freely available Landsat imagery and LCZ classification framework to map the cities. It provides chance for the public to access to the city data. However, the LCZ types are characterized mainly by the parameters of land cover ratio, building height, construction material, street H/W and vegetation(Stewart and Oke, 2012). The building information about pattern typology and layout typology are not considered so far, but these factors will influence the thermal

microclimate as well (Middel et al., 2014). It could be understood that LCZ is proposed under a homogeneous environment context, but lack of those information will bring difficulties to the architects and planners when they are required to locate and design a specific block in a typical local climate zone site.

The effect of urban development on local thermal climate is widely documented in scientific literature (Grimmond, 2007, Steeneveld et al., 2011). Beijing, as the capital of China, after 3000 years of evolution, now, it is a typical mega city that holds 21.5 million population. Various kinds of building typologies emerged during the urbanization progress, especially in the downtown area with long history.

Therefore, this paper used downtown area in Beijing as the study case, and aimed to discuss the effects of building typology (pattern and layout) on the thermal microclimate. In this research, Beijing's WUDAPT image provided samples selection reference. In addition, the overall average physiological equivalent temperature (PET) was used to assess the thermal environment in one LCZ site. PET is a single index enables a layperson to assess the thermal component of climate on the basis of personal experience, so it will be easy for architects and planners to understand (Matzarakis and Amelung, 2008).

The research steps included: (1) Chose samples in LCZ1 and LCZ2. (2) Classified the samples into different groups according to their building patterns and layouts. (3) Conducted simulation in ENVI-met V4 and outputted the climate data: air temperature, relative humidity, globe temperature, wind speed, wind direction, and the solar radiation. (4) Used Bio-met to calculate PET value in each modeling grid, and outputted the final consequence.

## Description of study area

### ***Beijing urbanization history***

Beijing is a political, cultural and international exchange center in China. It was built in 589 BC. Since 1953, Beijing's urban planning strategy was first proposed. There were four times of strategy adjustment, although each time a cycle was planned to inhibit the city expansion, Beijing still presents radical development mode now (Jing-qiu, 2001).

Historical documents shows that Beijing grew slowly during the period of 1932-1956, from 1956 to 1984, the speed was faster and the city began to expand along different directions. The rapid expansion began since 1984. Until the year of 1992, the construction of downtown area (Second and Third Ring Road) has been finished. During 1992 to 2000, the tendency of expansion eased, and the downtown area underwent second round of construction. After 2000, Beijing entered the period of fast urban expansion (HUANG Jie, 2014, Tian et al., 2011).

### ***WUDAPT of Beijing***



Figure 1 Beijing WUDAPT

The image of Beijing WUDAPT (Figure 1) in 2014 shows that LCZ1, LCZ2, LCZ3 mainly distributed in the center of Beijing, and the greening area mostly located out of the center.

Combined with urbanization history of Beijing, the WUDAPT pattern fitted well with the construction tendency under different phases of development.

As the WUDAPT image shows the LCZ type classification clearly and accurately, it is easy for architects and planners to understand the building geometry characteristics in the samples without the complicated calculation. This paper uses WUDAPT of Beijing in 2014 as reference, chose research samples for discussion based on it.

### ***Building typology in Beijing***

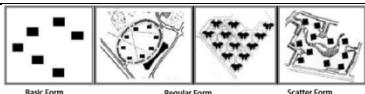


Figure 2 Pavilions Building Typology under Chinese Regulation



Figure 3 Courts Building Typology under Chinese Regulation

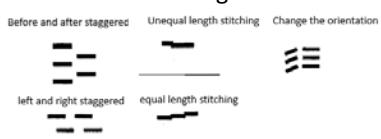


Figure 4 Terraces Building Typology under Chinese Regulation

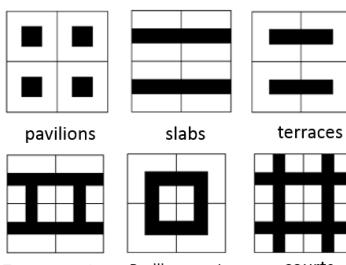


Figure 5 Western Building Typology

		Second Cycle and Third Cycle					
		LCZ1	Representative form	LCZ2	Representative form	LCZ3	Representative form
Pavilions	Regular	o		o		o	
	Scatter	v		v		v	
Terraces	Not aligned	v		v		v	
	Aligned	o		v		o	
	L	o		v		o	
	Polyline	o		v		o	
Courts	Semi-court	v		v		v	
	Court	o		o		v	

Figure 6 Beijing Building Typology

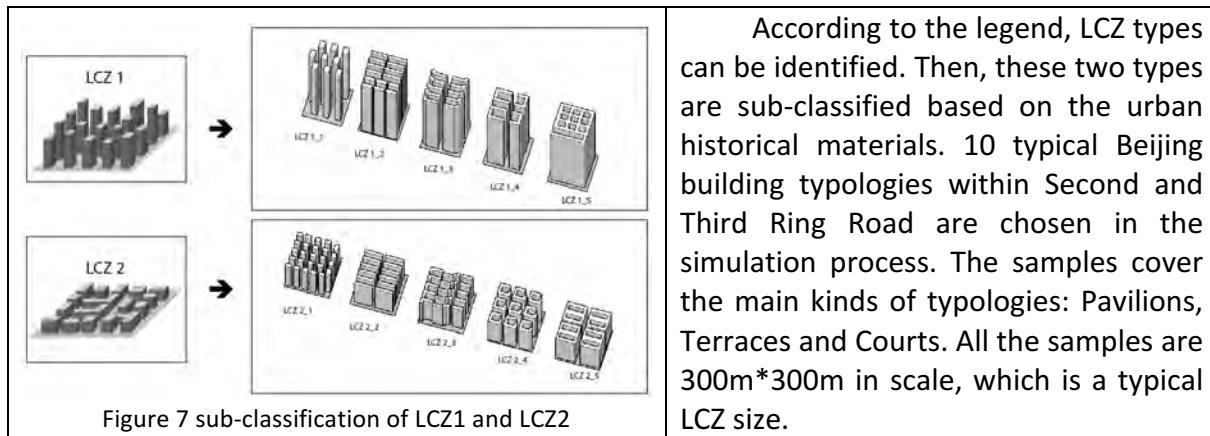
Building typology in this study and other documents refers to a set of buildings which have similarities in their form(Wood, 1968, Luperto et al., 2014). Normally, there are two dimensions of the word ‘type’. The first is the common one to understand, the usage of buildings, such as office building, residence, shopping mall and so on. The second one, defines it with geometry, service life, materials and surrounding of buildings. The research discusses under the background of climate change, building parameters involves second definition of the word ‘type’ which have closer relationship with context (Middel et al., 2014, Salvati, 2015). So the building typology in this research is defined according to the second perspective, and involved geometry factors. Figure 5 shows the traditional building typology in western countries (Martin and March, 1972, Ratti et al., 2003). Figure 2-5 shows the specific building typologies which corresponding to Chinese Regulation (zhiqiang, 2010).

Based on the image of Beijing WUDAPT and the historical materials, this paper summarizes building types within the range of Second Ring Road and Third Ring Road. Figure 6 shows the result of summary. Beijing has its own characteristic of building typology: There are more pavilion types in LCZ 1 than LCZ 2, but LCZ 2 contains more types of terrace typology. Both LCZ 1 and LCZ 2 have unique types of courts.

## **Methods**

### ***Choose sample***

The WUDAPT image gives clear description about the LCZ distribution over the whole city. Different colors of the pixel represents for different types of LCZ.



### **Simulation in ENVI-met**

ENVI-met, as an advanced simulation system that recreates the microclimatic dynamics of outdoor environment by addressing the interaction between climatic parameters, vegetation, surfaces, soil and the built environment. New features in ENVI-met V4 include simple forcing of air temperature and humidity in 2m level which needs simple input data, such as, initial temperature of atmosphere, specific humidity at model top and maximum and minimum values over a 24h cycle (Huttner and Bruse, 2009). This study used simple forcing mode and do not force any options during the simulation. Compared with other software, ENVI-met is particularly popular for its high temporal and spatial resolution, and it is based on the fundamental laws of fluid dynamics and thermodynamics, while other models are 3D radiation models (Ali-Toudert and Mayer, 2006).

Beijing typical summer weather is used to set up the configure document. The configuration is as below (SHI et al., 2012).

Setting	Output	
<b>Wind</b>		Air temperature
Wind speed measured in 10m height (m/s)	5.5	Air humidity
Wind direction (deg)	150	Wind velocity
Roughness length at measurement site	0.1	radiant temperature
<b>Temperature T</b>		
Initial temperature of atmosphere (K)	299	
<b>Humidity q</b>		
Specific humidity at model top (2500m, g/kg)	7	
Relative humidity in 2m (%)	61	
<b>Total Simulation Time (h)</b>	5	

Form 1 ENVI-met configuration setting

The model resolution is 2m\*2m, the base height is 0.75m on z axis direction. Version 250\*250\*30 is chosen when running the simulation.

### **Calculate the PET value**

PET is defined as the air temperature that is required to reproduce in a standardized indoor setting and for a standardized person whose core and skin temperatures that are observed under the conditions being assessed. Normally, the calculation includes two steps:

1. Calculated the thermal conditions of the body with MEMI for a given combination of meteorological parameters.

2. Inserted the calculated values for mean skin temperature and core temperature into the model MEMI and solved the energy balance equation system for the air temperature  $T_a$ . This final  $T_a$  is equivalent to PET.

In this study, PET was calculated through BioMet 1.01. BioMet 1.01 is a post-processing tool to calculate human thermal comfort indices which includes PMV/PPD, PET and UTCI. It directly interacts with the ENVI-met and does calculation based on the simulation data output by ENVI-met. Basically, BioMet summarizes the impact of four variables on human thermal sensation: air temperature, radiative temperature, wind speed and humidity. The study used mean PET value ( $PET_{mean}$ ) and the variation ( $\text{MAX}_{PET} - \text{MIN}_{PET}$ ) to compare both the overall situation and variation of samples.

## Result and discussion

### $PET_{mean}$

Ten typical Beijing LCZ1 and LCZ2 samples were involved in this simulation, the image outputted by BioMet showed clearly the space distribution of PET. Extracting PET value from each grid at 1.95 height, then calculating their  $PET_{mean}$ , to evaluate the performance of the sample.

Referred to Figure 8, by comparing two groups of LCZ1 and LCZ2, the  $PET_{mean}$  of LCZ2 was significantly higher than LCZ1. This was mainly caused by the average height of LCZ1 larger than LCZ2, followed by it, the building shadow area was larger. Therefore, LCZ1 received less solar radiation during 10 a.m.-13 p.m., which could provide more comfortable thermal environment to human.

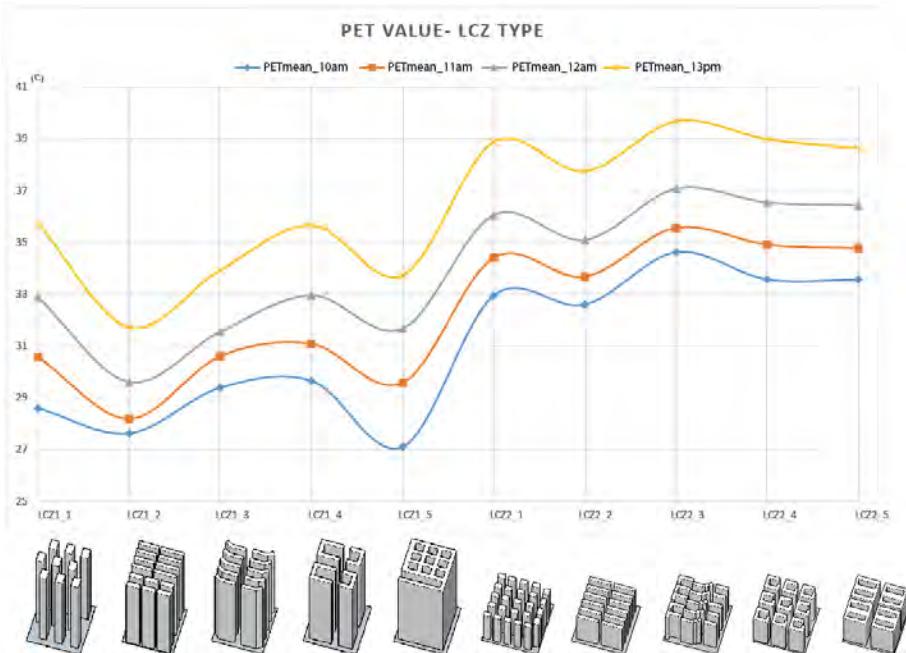
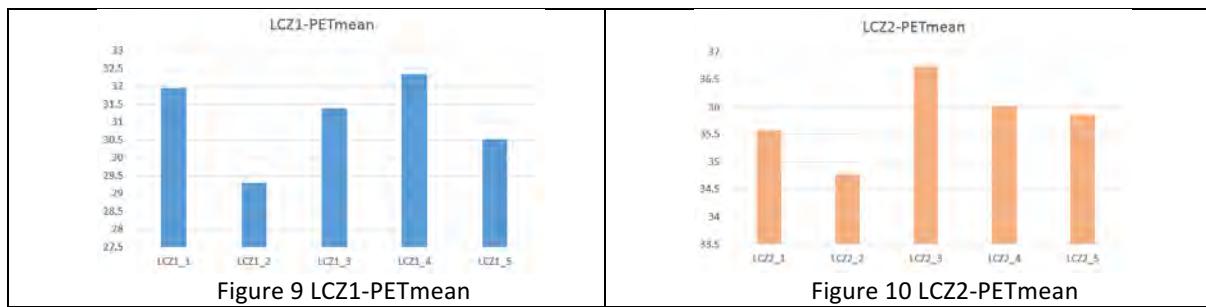
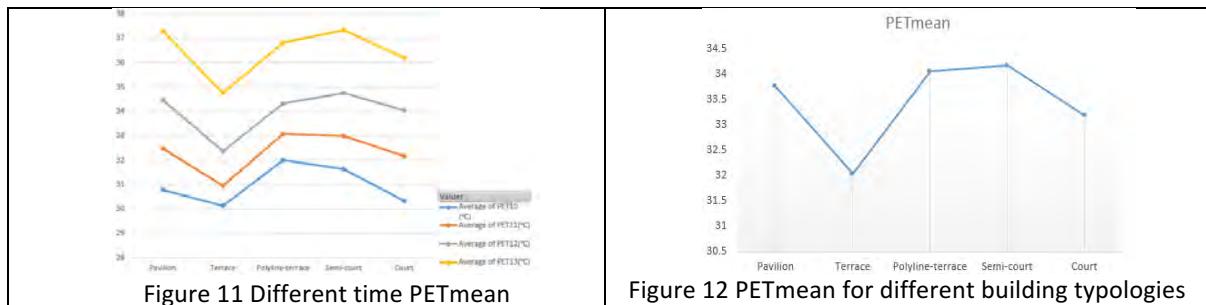


Figure 8 PET VALUE-LCZ TYPE



Discussing within the same LCZ type, different building typologies' performance was different. In the group of LCZ1, the pavilion typology (LCZ1\_2) has the lowest PET ( $29.0^{\circ}\text{C}$ ) during the simulation period. It means that people will only feel slightly warm by considering the influence of building layout typology that is terrace. While semi-court typology (LCZ1\_4) has the highest PET ( $32.3^{\circ}\text{C}$ ), people will feel warmer in this sample. In addition, in the group of LCZ2, pavilion typology (LCZ2\_2) also performs best with PET, whose value is  $34.8^{\circ}\text{C}$ . However, it is higher than the maximum value of LCZ1. At the same time, people in the polyline-terrace typology sample will feel the warmest.



Discussing within the same building layout typology, the terrace typology's performance is the best among all the typologies during the whole simulation period. On the other hand, the polyline-terrace, semi-court and pavilion typology have similar performance that PETmean is around  $34^{\circ}\text{C}$ .

It should be noticed that in the group of LCZ1 or LCZ2, semi-court typology has opening for better ventilation, while court typology is a closed building sample. However, the court typology's PETmean value is lower than semi-court typology. The reason for that is Beijing dry weather in summer and ventilation is less important than dryness in Beijing. While in humidity area, such as Hong Kong, Singapore, larger shading area still could help insulating solar radiation. That is why in Beijing, the court typology is a better choice than semi-court typology.

In summary, although LCZ classified different urban areas according to some geometry characteristics, the information it contains is not enough for architects and urban planners to design climatic response and sustainable buildings and cities. It could be seen from charts that even if in the same LCZ type, the effect of different building layout typologies is significant. The difference of microclimate between the best and worst samples is huge, under context of Beijing, terrace and court typologies are ideal solutions for LCZ1 and LCZ2 groups.

### Variation of PET

Based on the result of PETmean, this part will focus on discuss the building layout typology which has influences on PET value. Through three statistics of 1. Maximum mean value of the simulation period, 2. Minimum mean value of the simulation period, 3. Variation (MAX-MIN)

mean value of the simulation period, this part analyzes the extreme situation and how PET changes among all the samples.

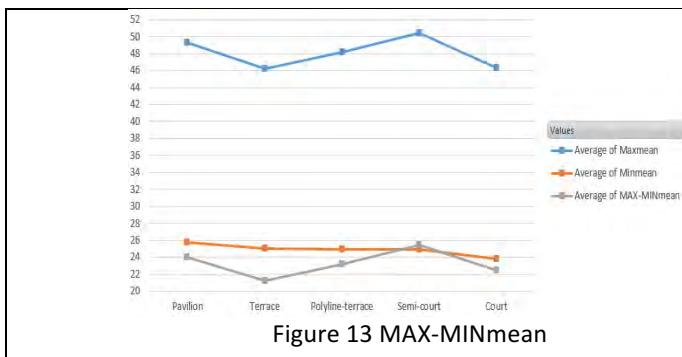


Figure 13 MAX-MINmean

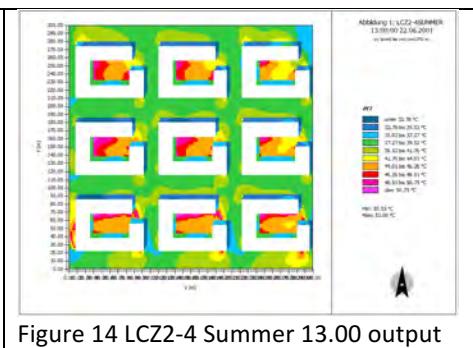


Figure 14 LCZ2-4 Summer 13.00 output

Figure 13 indicates that in terms of the minimum mean value of each sample, the PET value does not fluctuate a lot, while the maximum mean value is significantly different from each other. Terrace and court typology have lowest maximum mean PET value, conversely, semi-court typology has highest value which is over 50°C. People will feel extreme heat stress some places in these kinds of building samples. The pattern of MAX-MINmean is similar to the pattern of maximummean, the huge floating is accounted for the difference from highest PET value. For example, LCZ2\_4 is a typical Beijing semi-court building layout typology. In the courts space, most of the space is with high PET values, while in the street space, the PET is significantly lower. Therefore, the huge variation does not mean the diversity of microclimate in this simulation, it could not provide comfortable thermal environment for different groups of people in high density area.

### Conclusion and limitation

Climate change, urbanization are speeding up. The theory of urban planning should be modified response to this kind of change, otherwise, the city will undergo an unreasonable development, and become vulnerable in extreme weather. Under this context, Local Climate Zone is an infrastructure which could help architects and urban planners to understand better about how to design a climatic response block. So far, building height, building area cover, building density are included in LCZ classify criteria, these parameters will control the basic geometry characteristic of the samples. However, more parameters should be added into the system. This study firstly indicates Beijing, after a long time development, has its own classification building layout typologies. The general classification result does not proposed on the basis of Chinese building regulation and Beijing development history. The result from this study shows that, even within the same LCZ group, different build layout typologies will cause significant different microclimate situations. To release the urban heat stress in summer, terrace and court typologies are the ideal choices for Beijing, actually, courtyard is the traditional image of Beijing. On the contrary, semi-court and pavilion typology will cause extreme heat stress in summer. At the same time, compared with the factor of ventilation, shading is more efficient in providing a thermal comfortable environment.

The study is only a start of completing the LCZ system, in order to make a better use for architects and urban planners to make decision. There are two limitations of this study. Firstly, only use Beijing summer for sample, while Beijing's winter is cold and dry, sometimes uncomfortable for human living. Therefore, for Beijing, the PET value in winter is also worthy to study. Secondly, simulation only last for five hours, which could not take the night situation

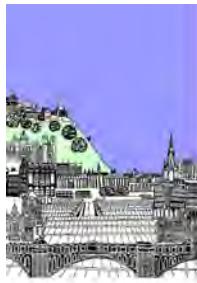
into consideration. After one night, the situation will change as the building itself will release heat in evening.

## Acknowledge

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## Reference

- Ali-toudert. F. & Mayer.(2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and environment*, 41, 94-108.
- Grimmond, S.(2007). Urbanization and global environmental change: local effects of urban warming. *The Geographical Journal*, 173, 83-88.
- Hallegatte, S.(2009). Strategies to adapt to an uncertain climate change. *Global environmental change*, 19, 240-247.
- Huang Jie, L.T., Zhang Guo Qin, Li Xin Hu. (2014). Comparative Analysis of the Urbanization Dynamic Characteristics of the Three Major Urban Agglomerations in China. *CHINA POPULATION, RESOURCES AND ENVIRONMENT*, 24, 8.
- Huttner, S. & Bruse, M. (2009).Numerical modeling of the urban climate—a preview on ENVI-met 4.0. 7th International Conference on Urban Climate ICUC-7, Yokohama, Japan.
- Jing Qiu, Z.(2001). Spatial Features of Beijing City' s Development History. *Journal of Beijing Union University*, 15, 3.
- Luber,G. & Mcgeehin,M. (2008). Climate change and extreme heat events. *American journal of preventive medicine*, 35, 429-435.
- Luperto, M., Quattrini Li, A. & Amigoni, F. (2014). A System for Building Semantic Maps of Indoor Environments Exploiting the Concept of Building Typology. In: BEHNKE, S., VELOSO, M., VISSER, A. & XIONG, R. (eds.) *RoboCup 2013: Robot World Cup XVII*. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Martin, L. & March, L. (1972). *Urban space and structures*, Cambridge University Press.
- Matzarakis, A. & Amelung, B. (2008). Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans. *Seasonal forecasts, climatic change and human health*. Springer.
- Middell, A., H B, K., Brzel, A. J., Martin, C. A. & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, 122, 16-28.
- Milis, G., Ching, J., See, L., Bechtel, B. & Foley, M.(2015). An introduction to the WUDAPT project. 9th International Conference on Urban Climate, Toulouse.
- Ratti, C., Raydan, D. & Steemers, K. (2003). Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and buildings*, 35, 49-59.
- Rizwan, A. M., Dennis, L. Y. C. & Liu, C. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, 20, 120-128.
- Salvati, A.(2015). Urban morphology and energy performance: The direct and indirect contribution in mediterranean climate. *PLEA 2015*.
- Shi, Y., Ren, C. & NG, E. (2012).Analysis of Urban Design Strategies Based on the Outdoor Wind Environment and Thermal Comfort: A Case Study of Beijing Xidan Commercial District. *Urban Planning Forum*, 2012. 92-98.
- Steeneveld, G., Koopmans, S., Heusinkveld, B., Van Hove, L. & Holtslag, A. (2011). Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *Journal of Geophysical Research: Atmospheres*, 116.
- Stewart, I. D. & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, 93, 1879-1900.
- Tian, G., Jiang, J., Yang, Z. & ZhangG, Y. (2011). The urban growth, size distribution and spatio-temporal dynamic pattern of the Yangtze River Delta megalopolitan region, China. *Ecological Modelling*, 222, 865-878.
- Wood, M. (1968). The English mediaeval house.
- Zhiqiang, W. (2010). Theory of Urban Planning. China Architecture & Building Press.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## EdenApp Thermal Comfort: A mobile app for measuring personal thermal comfort

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**Abstract:** Currently, many researchers focus on how to apply Predicted Mean Vote (PMV) and Adaptive Comfort (AC) models to different climatic zones and types of buildings to study how specific environmental elements or forms of behaviour influence participant's thermal choice. However, most of the studies focus on modelling thermal comfort which was based on average group data statistics and did not localise the thermal difference at individual levels. In addition, expensive professional sensors and closed source data collection tools increased the difficulty for new researchers to develop customized long-term personal data collection systems. As a result, we developed EdenApp-Thermal Comfort, an open-source mobile app which can record participants' individualised thermal comfort responses and local environmental data. These forms of personalised data can be uploaded onto the EdenApp server and used for further research into individual and group thermal comfort analysis. This paper discusses the significant benefits of modelling personal thermal comfort, when compared with traditional methods. It also describes the newly formed EdenApp data collection platform and its use for a pilot study on recording personal thermal comfort amongst students.

**Keywords:** personal thermal comfort recording, Thermal sensation, Adaptive model, PMV

### Introduction

Thermal comfort is a term used to describe occupant satisfaction with the thermal environment (ASHRAE, 2013). Currently 'adaptive thermal' is the most popular model in use as it is not based on steady state human comfort votes in laboratory conditions (Nicol & Roaf, 2017). Instead it focuses on the use of non-mechanised passive cooling systems, which are more environmentally sustainable. Furthermore, it considers occupants' behaviour, clothing and the effect of these sessions as important factors to thermal perception. In contrast, the historic Predicted Mean Vote (PMV) model focused on laboratory reports on respondents' comfort to satisfy mechanically operated energy building systems. However, there are still limitations in using the adaptive model. Firstly, it can only be used in buildings that adopt passive cooling systems. Also, occupants' metabolic rate should range from 1.0-1.3 met, whilst clothing be within 0.5 to 1.0 clo. Finally, outdoor temperature should have a 10 to 33.5 degree range. The adaptive model also does not explain clearly how the linear regression analysis model incorporates all factors of measurement. Both the Adaptive and PMV models use forms of top-down statistical analyses which focus on average group data. Conversely, is it possible to use a bottom-up simulation model that seeks to construct a fundamental personal thermal comfort pattern to explain how individual adaptive behaviour might affects thermal sensation and vice versa?

In addition, conventional questionnaire and measurement tools can be time-consuming and costly which makes personal measurement and data collection process more difficult. This paper discusses how the use of apps connected to cheaply purchased ‘off-the-shelf’ sensors might be an effective way of surveying personal thermal comfort, and how these apps may be developed for further environmental measurements which are required for accurate personalised thermal comfort readings.

The Predicted Mean Vote (PMV) analysis method was developed by Fanger in 1970 (Fanger, 1970). Based on a series of experiments and the heat balance model, he summarised that the thermal sensation vote could be predicted by six parameters: air temperature, radiant temperature, relative humidity, air velocity, clothing insulation and metabolic rate. Current research questions whether the PMV is the best estimate of respondents' personal thermal sensation levels. Humphreys, Nicol et al. (2007) found that the results from PMV analyses suggested that respondents were warmer than they actually felt. Thus actual thermal comfort was found to be cooler than PMV predictions. Van Hoof (2008) suggested that PMV was just an approximation result from a ‘natural’ environment setting and lacked individual differences. Stoops (2006) thought that the human effort in improving artificial conditioning system was minimizing the use of our thermoregulatory system. Thus, more work is needed to focus on how the freedom of environment control and personal behaviour change affect thermal comfort.

Nicol and Humphreys (1973) combined a series comfort vote data and found out that different social customs and clothing could be important factors to consider. They generated a thermal regulatory system which described subjective warmth as an active influence on thermal comfort. De Dear, Brager et al. (1998) concluded from their findings that the adaptive model has three interlinked aspects: physiological, psychological and behavioural. In his report, he also proposed two adaptive thermal comfort prediction models; one for centrally controlled building and another for naturally ventilated buildings. The modified version of the latter was included in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 55 (2004) and was gradually incorporated into the criteria for ASHRAE standard 55 (2013) and EN 15251(2007).

Whilst both the PMV and adaptive models predict thermal sensation in different building types and climate zones, these models still work on group thermal preference measurements and not those of individuals. They are built using data from experiments or field studies, to establish average mapping between environmental parameters and human thermal comfort reports. These models give group responses, but cannot accurately predict individual preferences in personalised spaces such as student accommodation, hotel rooms, or personalised office spaces (Gao and Keshav, 2013, Zhao, Zhao et al., 2014). Due to individual physiological differences and subjective thermal sensations, respondents will have different levels of thermal sensation (Liu, Lian et al., 2007) and these can change on a seasonal basis. Even when subjects work in a comfortable thermal environment where the  $PMV = 0$ , 5% of them will still feel uncomfortable. Is it therefore possible to build a personal thermal comfort model?

Based on the PMV heat balance model, Zhao et al. (2014) proposed a rational thermal assessment model using learning methods to present personalized thermal comfort in ordinary offices. They also validated its prediction result through a three-month field study. Jiang and Yao (2016) treat the personal thermal sensation model as a classification problem between different parameters. They used the C-support Vector Classification (C-SVC) algorithm to learn each occupant's thermal preference first and finally calculated the

predicted result of thermal sensation. Similarly, Ghahramani, Tang et al. (2015) used Bayesian network train the thermal factors data and finally got a prediction result which had 70.14% accuracy of thermal sensation. These projects focused more on how to construct suitable algorithms such as machine learning to fit the input and output, to achieve a good personalised prediction result. This was successful, but did not take into account the effects of personal adaptive behaviour, such as opening or closing windows, clothing levels, or the switching on or off of heating systems, on thermal sensation.

In addition, to accomplish the environmental measurement process, most of the above research used digital tools instead of manual questionnaires. The use of complicated equipment and field studies affect the integrity of thermal sensation research. Instead of conducting repetitive studies on changes in thermal sensation, new technologies using data logging of environmental factors, and digital thermal responses and the tracking of adaptive behaviour can now be easily introduced. This is important not only for researchers but also for engineers, as new technologies for measurement at personal level using micro sensors and relevant forms of calibration need to be developed. No literature was found describing the use of portable measurement tools in the logging of the personal experience of thermal sensation.

In this project, our goals were: firstly; to develop a cheap sensor set and effective mobile app to collect subjective and environmental data. Secondly, to use field study results to analyse the individual thermal sensation difference from ten subjects. Thirdly, to compare the sensation vote with the prediction result from PMV model, and finally to suggest future areas for research developments in the production of personal thermal assessment apps.

## **Methodology**

### ***Sample selection and field studies***

By the completion of this paper, the field study was still being undertaken. Thus, the data presented was incomplete and from only two of the proposed ten subject responses. The study was conducted in student bedrooms within new Edinburgh University student accommodation. Each study bedroom had adjustable central heating and operable windows that subjects could adapt to their individual thermal preference. Field studies were being conducted from April to July 2017 with subjects conducting assessment measurements over a two-week period.

Of the ten subjects, there are five of each sex. All of them will be briefed on the study aims, acquainted with the instruments and trained to understand the measurement processes required first. All the subjects have lived in Edinburgh for at least two years, and thus would have acclimatization to the local temperate climate conditions.

Before the commencement of the exercise, the 'EdenApp-Thermal Comfort' mobile application was installed onto the subjects' smartphones and sensors (SensorTag and Testo 405i anemometer) were given to each subject. After adequate training on app and sensors use, subjects were expected to undertake the two-week period of thermal assessment recording. Each subject will fill in at least six digital questionnaire survey responses daily. Each questionnaire readings would be expected to take a maximum of 2 minutes to complete. The questionnaire (Figure 1) asked subjects for subjective data (Step 1-5), and guide respondents connect with the sensors to measure environmental data (Step 6). These data were then automatically uploaded to our 'cloud' server (Figure 2), where they would be used for future

statistical analysis. After the survey, subjects would also be provided with the results of their analysed questionnaire responses and measurements.

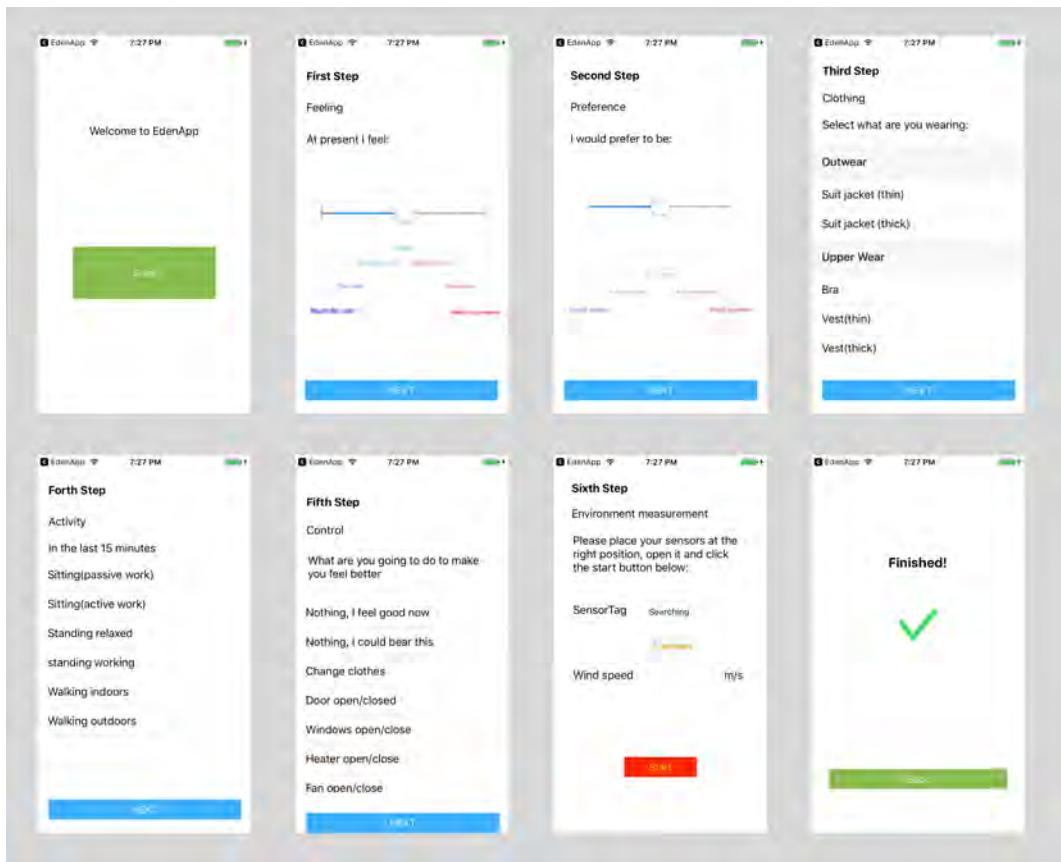


Figure 1. Work flow of the questionnaire

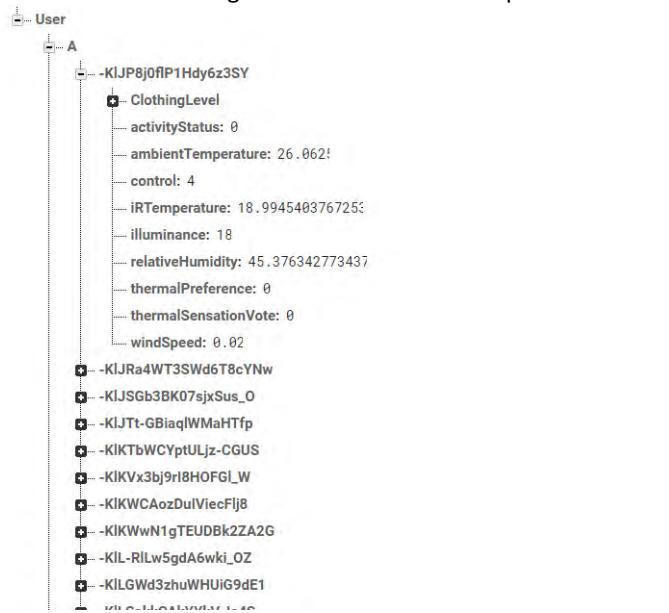


Figure 2. Database on EdenApp cloud server

### **App-based questionnaire and digital measurement**

When occupants first use EdenApp-Thermal, they need to register an account and type their personal information (gender, age and nationality) into the app. As the questionnaire is merged into the app, occupants can finish the questionnaire quickly. The digital survey uses

the ASHRAE 55-2013 format which requires details of clothing insulation, metabolic rate and 7-level scaled thermal sensation vote. Questionnaire step 6 covers measure environment parameter measurements: Air speed at 1.1-meter above ground will be measured using Testo 405i hot-wired anemometer. As we haven't got the Bluetooth document from Testo, the data needs to be manually typed into the app. Other environmental data will be measured using the SensorTag placed at 1.1-meter above ground and with a clear radius of 1m around. After clicking the open button of SensorTag, EdenApp will automatically check the connection with the SensorTag and record current environment data. Table 1 shows the subjective data collected from app and Table 2 shows the environmental data collected from the sensors. In comparison to ASHRAE 55's current use of more technical, expensive equipment, EdenApp-thermal is a cheaper alternative and can deliver basic results.

### ***Data processing***

After the data collection process in the future, at least 840 data points could be downloaded from our database and saved as CSV format. Each column of the data file was divided by parameter name. First, PMV-PPD was calculated by the ASHRAE 55-2013 standard procedure. Second, to examine the statistical significance of the data, correlation and regression models were calculated by using Prism, an analytical software programme. Once all data was recorded, the difference between personal thermal sensation recorded the predicted PMV and actual mean vote (thermal sensation vote) would be compared.

Table 1. Subjective data collected from EdenApp-Thermal

Information	Reference	Scale	Range
Clothing level	ASHRAE garment insulation	0.01	clo: From 0 (naked) to n (sum)
Activity level	ASHRAE metabolic rates for typical tasks	0.1	Met: seated (0.8-1.0), standing (1.2-1.4), walking about (1.7-2)
Thermal sensation Vote	7-scale thermal sensation vote	Continuous	Continuous from -3 to +3: Cold (-3), Cool (-2), Slightly cool (-1), Neutral (0), Slightly Warm (+1), Warm (+2), Hot (+3)
Thermal preference	5-point satisfaction scale	1	From prefer much warmer (+2) to much cooler (-2)
Adaptive behavior	ASHRAE K-2 satisfaction survey	/	Adjust: Nothing, Change clothes, Door, Windows, Heater, Fan open/closed

Table 2. Environmental data collected from the sensors

Environment parameters	Range	Range (ASHRAE)	Accuracy	Accuracy (ASHRAE)
Air temperature (HDC1000)	-40C° to 125C°	10C° to 40C°	±0.2C° (max)	±0.2C°

Inferred temperature (TMP007)	0°C to 60°C	10°C to 40°C	±1°C (max)	±1°C
Relative Humidity (HDC1000)	0% to 100%	25% to 95%	±3%	±5%
Wind speed (Testo 405i)	0 to 30 m/s	0.05 to 2 m/s	±5%	±0.05m/s

## Results

### ***Thermal environment of selected accommodation in Edinburgh***

Figures 3 and 4 show histograms of the Thermal Sensation Vote (TSV) from the two subjects whose records are presented in this paper.

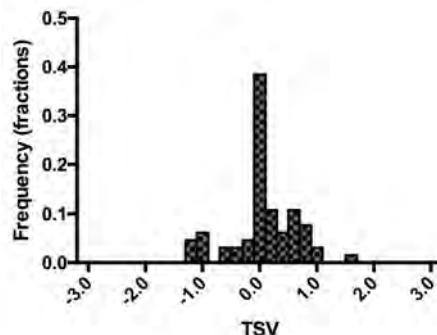


Figure 3. Histogram of Thermal Sensation Vote (from five subjects)

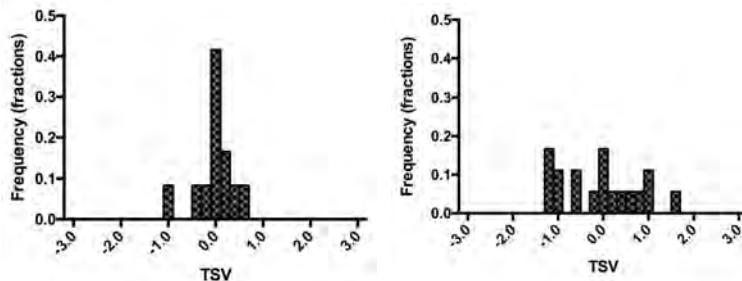


Figure 4. Histogram of Thermal Sensation Vote (left: subject 1, right: subject 2)

Most of the vote values are distributed between -1 and 1 which stands for slightly cold and slightly warm. The subjects are mostly felt well with their room's thermal environment. From Figure 4, the thermal sensation vote from subject 1 is similar with the trend of the whole group in Figure 3. However, the feedback from subject 2 shows a different pattern where thermal vote is separately distributed between -1 with 1. Although the thermal environment is acceptable to subject 2, it shows this subject is more thermal sensitive than others. This individual difference helps to build personal thermal comfort pattern in the future.

### ***Personal difference in indoor environment***

Table 3 and Figure 5 shows individual difference of their preferred temperature and relative humidity. Subject 2 have a wider acceptable range to temperature and humidity, but subject 2 prefer the room cooler and dryer. Table 4 shows which environment parameter is significantly related with thermal sensation vote and the correlation among these parameters.

Table 3. Indoor operative temperature and relative humidity

subject number	T <sub>o</sub> (C°)			Rh <sub>in</sub> (%)		
	average	minimum	maximum	average	minimum	maximum
1	26.5	23.5	28.4	23.5	18.4	34.3
2	25.2	22.1	26.8	28.5	24.5	33.5

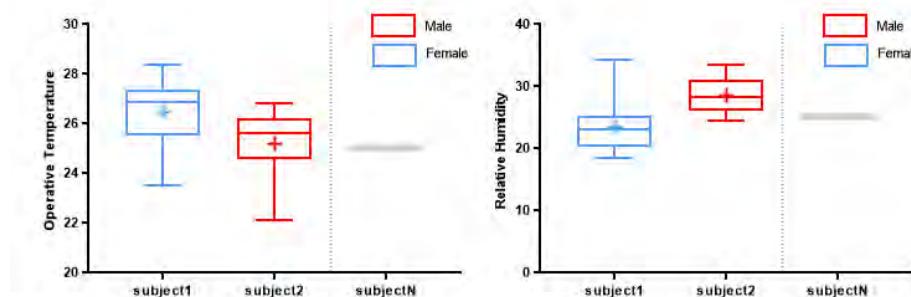


Figure 5. Individual difference of operative temperature and relative humidity

Table 4. Personal correlation of each parameters

Subject	Variables which have significance with TSV	other correlation
1	T <sub>a</sub> , T <sub>IR</sub> , Rh	T <sub>a</sub> & T <sub>IR</sub> , Rh & T <sub>a</sub> , MET & CLO
2	T <sub>a</sub> , T <sub>IR</sub>	T <sub>a</sub> & T <sub>IR</sub>

#### Comparison between TSV and PMV

Figure 6 compared the PMV with TSV from subject 1. On the left side, both lines have a p-value less than 0.05 which means the linear regression line well fit with the data. The black line ( $y = 0.15x - 3.95$ ) which stands for the actual thermal sensation vote has a lower slope than PMV ( $y = 0.28x - 9.06$ ). Although as the operative temperature became higher, PMV had similar prediction to the actual vote, from the right side, as TSV increase PMV still underestimates respondent's thermal sensation.

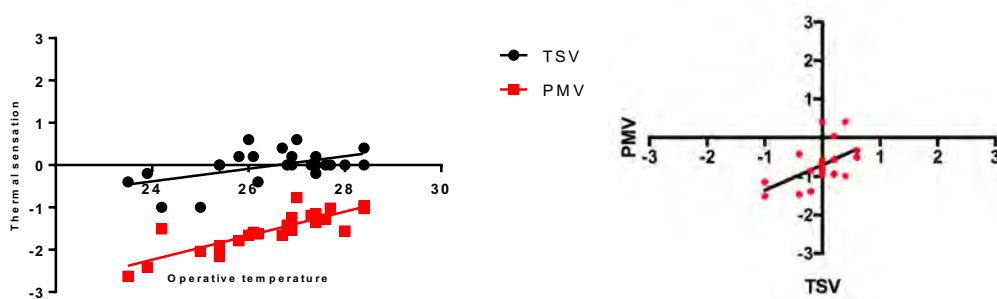


Figure 6. The comparison between TSV and PMV from respondent 1.

#### Interim conclusions

This paper presents a cheap and effective personal thermal measurement tool. There are several points that could be developed and improved next as in relation to the project:

1. Lack enough data. As the study has not finished, the data is too limited to make any conclusions. But it was successfully used by respondents as a prototype of cheap thermal measurement tool to quickly record personal thermal comfort data.

2. The customisation of the sensors being used, instead of using SensorTag and Testo 405i. This is critical as mean radiant temperature (or globe temperature) cannot be measured with current sensors. It is an important variable particularly in hot climates where radiant heat can significantly influence comfort perception.
3. The adoption of continuous environmental recording in place of the current two-minute survey, as this will give more accurate and detailed recording.
4. Also, there is need to choose better control and experimental subject groups to undertake the specific thermal comfort reporting.

## **Discussion**

Thus far, depending on the current collected data, we have found using EdenApp thermal as a measurement tool that students in their accommodation do have individualised thermal preferences. They prefer to maintain their indoor environment to best suit their thermal preference. Secondly, the PMV model cannot accurately predict individual thermal sensation in a highly-personalised space such as a student room. It therefore makes sense to develop a personal thermal sensation model both to improve localised energy efficiency and to communicate to students how their actions can affect energy efficiency. Finally, Although the field study has not finished and the analysis is from two respondents, EdenApp-Thermal Comfort with its attached sensors demonstrates how a contemporary mobile app can enable researchers the ability to record and analyse personalised thermal comfort responses and simultaneously track related environmental measurements such as temperature and humidity. The use of EdenApp-Thermal Comfort and cheaply purchased sensors also enables the development of a 'ground up data collection model' for environmental analysis research, and allows for the development of new digital methods for analysing and predicting occupants' comfort levels.

## **References**

- ASHRAE (2013). ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy. (American Society of Heating, Refrigerating and Air-Conditioning Engineers).
- De Dear, R. J., et al. (1998). Developing an adaptive model of thermal comfort and preference/Discussion. *ASHRAE Transactions* 104 145.
- Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering*.
- Gao, P. X. and S. Keshav (2013). SPOT: a smart personalized office thermal control system. Proceedings of the fourth international conference on Future energy systems, ACM.
- Ghahramani, A., C. Tang and B. Becerik-Gerber (2015). An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling. *Building and Environment* 92 86-96.
- Humphreys, M. A., J. F. Nicol and I. A. Raja (2007). Field studies of indoor thermal comfort and the progress of the adaptive approach. *Advances in Building Energy Research* 1(1) 55-88.
- Jiang, L. and R. Yao (2016). Modelling personal thermal sensations using C-Support Vector Classification (C-SVC) algorithm. *Building and Environment* 99 98-106.
- Liu, W., Z. Lian and B. Zhao (2007). A neural network evaluation model for individual thermal comfort. *Energy and Buildings* 39(10) 1115-1122.
- Nicol, J. F., & Roaf, S. (2017). Rethinking thermal comfort. *Building Research & Information*, 1–5.
- Stoops, J. L. (2006). Indoor thermal comfort, an evolutionary biology perspective. Lawrence Berkeley National Laboratory.
- Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all? *Indoor air* 18(3) 182-201.
- Zhao, Q., et al. (2014). A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application. *Building and Environment* 72 309-318.

# Community Energy

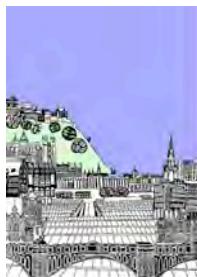
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## Achieving Energy Efficiency in Communities with Solar PV in the Developing Economy

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**Abstract:** Smart cities across the world are relying on solar to suffice their energy needs. A smart city has at least 10% of electricity generated by renewables. Cities see an expansion both vertically and horizontally. Vertical growth needs higher energy in terms of equipments like pumps, lifts etc. To cater to their high energy demand, huge electrical infrastructure is needed. Self sustainable communities are planned to address the issue of energy crisis. As solar energy is the mantra of the day, provision of roof top PV solutions for electricity generation has a bright future. The functioning of common community areas like street lights, corridor lights, lifts and water pumps are likely to be easily addressed by the electricity generated from Solar Photo Voltaics (PV) during day time. Due to vertical growth, the area available for roof top installations is restricted. To top it, there are other challenges such as availability of south facing and shadow free areas. Proper planning can overcome such challenges. To substantiate this statement, data was collected from a residential community in the pilot smart city area in Pune city, Maharashtra, India. The analysis compared the electricity consumption scenarios for common areas pre and post the installation of roof top Solar Roof Top PV. The comparative analysis of the data was done for the said scenarios and the inference was drawn upon the benefits of roof top solar PV for use in common community areas. The inference was validated theoretically for another similar community which yielded the same results. The paper thus sends a strong message that use of roof top solar PV is one of the best solutions for using the community energy efficiently. Also, it suggests the use of Building Integrated Photo Voltaic (BIPV) as the future of new construction business.

**Keywords:** Community, Solar PV, Electricity Consumption, BIPV

### Introduction

The primary energy demand in India has grown from about 450 million tons of oil equivalent (toe) in 2000 to about 770 million toe in 2012. This is expected to increase to about 1250 (estimated by International Energy Agency) to 1500 (estimated in the Integrated Energy Policy Report) million toe in 2030. To match the expected increase in energy demand, the Government is promoting greater use of renewable in the energy mix mainly through solar and wind. The use of solar energy for generating electricity is well known. In India, the high cost of installation of solar PV systems till very recent times discouraged many from taking the solar way to generate electricity. With the policies of the present governing body in the country, there is an unprecedented encouragement provided to the common people for installing solar PV systems. A plethora of affordable solar related products have been brought in the Indian market by various manufacturers. Easing of the statutory systems for installation of Solar Roof Top Photo Voltaic (SRTPV) Systems and provisions for availing

subsidies after the installation are also steps towards more such installations being seen around. Generating electricity on one's own site by using Solar PV and consuming it has seen a reduction in the electricity units utilised from the grid. The electricity bills of such users have reduced as a result. This is very encouraging for those who are Solar PV enthusiasts. It is believed to be very beneficial in the long run, both economically and environmentally. A reference to the official website of the Ministry of New and Renewable Energy (MNRE), Government of India (GoI), and the calculations presented therein for SRTPV installations indicate that installation of 1KWp system for a life time of 25 years will reduce carbon emissions by about 30 tonnes and is equal to planting 57 teak trees over lifetime ([http://solarrooftop.gov.in/Grid/financial\\_tool/2](http://solarrooftop.gov.in/Grid/financial_tool/2)). Government of India has undertaken a two pronged approach to cater to the energy demand of its citizens while ensuring minimum growth in CO<sub>2</sub> emissions, so that the global emissions do not lead to an irreversible damage to the earth system.

Energy Efficiency is using less energy to provide the same service. Improvements in energy efficiency are generally achieved by adopting a more efficient technology or production process or by application of commonly accepted methods to reduce energy losses. International energy Agency says that 'Energy efficiency is key to ensuring a safe, reliable, affordable and sustainable energy system for the future. It is the one energy resource that every country possesses in abundance and is the quickest and least costly way of addressing energy security, environmental and economic challenges. While energy efficiency policies are becoming a key part of the global energy market, there remains vast untapped potential.' Energy efficiency is one of the easiest and most cost effective ways to combat climate change clean the air we breathe, improve the competitiveness of our businesses and reduce energy costs for consumers. Energy efficiency and renewable energy are said to be the twin pillars of sustainable energy policy and are high priorities in the sustainable energy hierarchy. In many countries energy efficiency is also seen to have a national security benefit because it can be used to reduce the level of energy imports from foreign countries and may slow down the rate at which domestic energy resources are depleted. Efforts are being made to efficiently use the energy in the demand side through various innovative policy measures under the overall ambit of Energy Conservation Act (EC Act) 2001. The EC Act was enacted in 2001 with the goal of reducing energy intensity of Indian economy. Bureau of Energy Efficiency (BEE) was set up as the statutory body on 1st March 2002 at the central level to facilitate the implementation of the EC Act.

The authors believe that the installation of SRTPV is a step towards demand side management. Such an installation can reduce load on the existing state electricity grid and reduce transmission and distribution losses, thereby requiring less energy at the consumer point than that is being presently supplied.

### **Limitations of the Study**

The study is specific to the pilot smart city area of Aundh – Baner - Balewadi situated in Pune City, Maharashtra, India. Out of the three zones of Aundh, Baner and Balewadi, the authors have chosen Balewadi and Baner, as data collection went smoothly in these areas and people's perception for SRTPV was found to be positive. Generalising the results for the rest of the country is not aimed through this study as there are constraints of availability of solar irradiation, south facing areas and shadow free areas in different places which are the crux of the SRTPV installations. The study is based upon:

1. Scope and samples selected for the study.

2. The analysis is done on the data available from the considered samples regarding their electricity consumption pre and post Solar Roof Top PV installation.
3. Spaces available on the roof top of the samples selected. These spaces were majorly found to be occupied by solar water heater.
4. The outlook of the residents of the samples selected for residential communities.

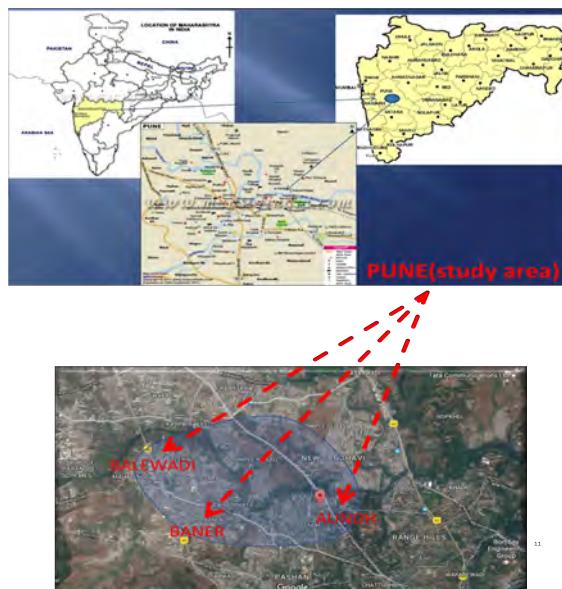


Figure 1: Location Map showing the pilot smart city area of Aundh-Baner-Balewadi

### Statement of the Problem

Literature on use of solar energy as a renewable means, its advocacy through use of Solar PV and its enormous benefits towards energy efficiency, propagating green buildings as well as less carbon dioxide emission is widely read and published in many books and journals alike. Yet, after going through the literature and analysing its application in practical scenarios, the authors felt the need to document the practical use of Solar PV systems in residential communities. While some communities felt the initial installation costs of the system to be high, many also accepted that the system had long term benefits.

### The Study

The study was conducted between 2016 and 2017 over a period of about 12 months. The pilot study was conducted in the months of Oct-Nov 2016. The study showed that one residential community that had installed the SRTPV system had seen very encouraging results by reduction in the amount of electricity bill issued by the State Electricity Distribution Company. To strengthen and confirm the initial predictions of the study, the authors selected 3communities that have installed the SRTPV System across the city of Pune. One sample was from the Baner-Balewadi area. The authors investigated what would be impact of implementation of such a system in the pilot smart city mission. After analysis of the details provided by them regarding the reduction in the amount of electricity bills, it is found that the installation of the SRTPV systems benefits the community by reducing its energy consumption from the state electricity grid. The moment we generate electricity on site, we help in the reduction of transmission and distribution losses. Reducing such losses brings in an efficient system. Other communities are thereby inspired to go the solar way for achieving energy efficiency. The purpose of the study, therefore, is to present the

achievement of energy efficiency in residential communities and propagate use of Solar Roof Top PV systems. Besides, the study reasons out why certain communities do not opt for Solar PV. The study is also widened to know whether any shortcomings in the installation can be overcome by other active and passive techniques of harnessing solar energy.

### **Research Question**

Based on the authors' initial study, the research question framed is stated as:  
Is the installation of Solar Roof Top PV system helpful in achieving energy efficiency in communities? What can be the constraints towards this achievement and what can be the solutions for them?

### **Research Objective**

The research question led to the following objectives which the authors wanted to find out more about.

1. To prove and convince the importance of installation of Solar Roof Top PV system in community areas to achieve energy efficiency. This was also done to enhance our knowledge in understanding what deterred the communities from installing the system.
2. To validate if the installation is resulting in reduction of electricity usage from the electricity grid and if energy efficiency is being achieved.
3. To know what active and passive technologies can be implemented to make the communities energy efficient.

Based on the comparative analysis of the data collected from the 3 residential communities in the city, the following hypotheses were formulated and tested.

#H1. Installation of Solar Roof Top PV System is likely to reduce the electricity consumption from the grid thereby reducing the amount of electricity bills.

#H2. Calculations for Solar Roof Top PV system for another community validate the study done in the selected sample communities.

### **Research Methodology**

The science of the method in which the research is conducted is the research methodology. The authors identified samples, research instruments and research methods for reaching the research objectives.

**a. Sample Selection:** The authors selected 3 samples for the said study for which complete data was available. The samples are chosen as they fit closer to the scheme of definition of communities whereas the other residential projects are more of standalone buildings.

**b. Research Instruments:** The research instrument contained collection of electricity bills of the communities, pre and post installation of the Solar Roof Top PV System.

**c. Research Method:** The residential community managements were assured that the data would be used purely for academics resulting in authentic data collection.

### **Data Analysis**

The data of electricity bills before and after the installation of the Solar Roof Top PV System was compared with regards to the total energy requirements, the total capacity of Solar

Roof Top PV System installed, the reduction in usage of the grid supplied electricity, reduction in the electricity bills and the units generated by the Solar Roof Top PV System.

### **Data Collected for Guruprasad Housing Community (GHC)**

Table 1 History for Electricity Consumption for GHC pre and post SRTPV installation done in Nov 2016

Bill Month	Consumption Units	Bill Amount	Amount Paid
Mar-17	1,631	21,900.00	36,240.00
Feb-17	2,534	36,550.00	32,470.00
Jan-17	2,239	32,740.00	46,050.00
Dec-16	3,167	46,450.00	50,390.00
Nov-16	3,611	50,390.00	41,990.00
Oct-16	3,104	42,360.00	37,610.00
Sep-16	2,691	37,930.00	19,240.00
Aug-16	1,506	19,410.00	8,530.00
Jul-16	799	8,610.00	11,800.00
Jun-16	961	11,910.00	11,410.00
May-16	946	11,520.00	12,490.00
Apr-16	1,030	12,600.00	14,550.00

The occupancy of the community increased after July 2016, increasing the consumption units since August 2016. This motivated the community to opt for SRTPV systems.

### **Data Collected for Nandan Prospera Housing Community (NPHC)**

Table 2 History for Electricity Consumption for NPHC pre and post SRTPV installation done in Oct 2016

Bill Month	Consumption Units	Bill Amount	Amount Paid
Mar-17	0	55	0
Feb-17	0	55	0
Jan-17	0	55	0
Dec-16	0	55	790
Nov-16	0	791.5	58,810.00
Oct-16	4,138	59,321.26	78,490.00
Sep-16	5,585	79,174.07	61,780.00
Aug-16	4,199	62,323.19	65,800.00
Jul-16	4,522	66,365.32	94,300.00
Jun-16	6,251	95,125.13	1,31,880.00
May-16	8,348	1,33,024.91	1,10,420.00
Apr-16	6,946	1,11,385.80	1,09,130.00

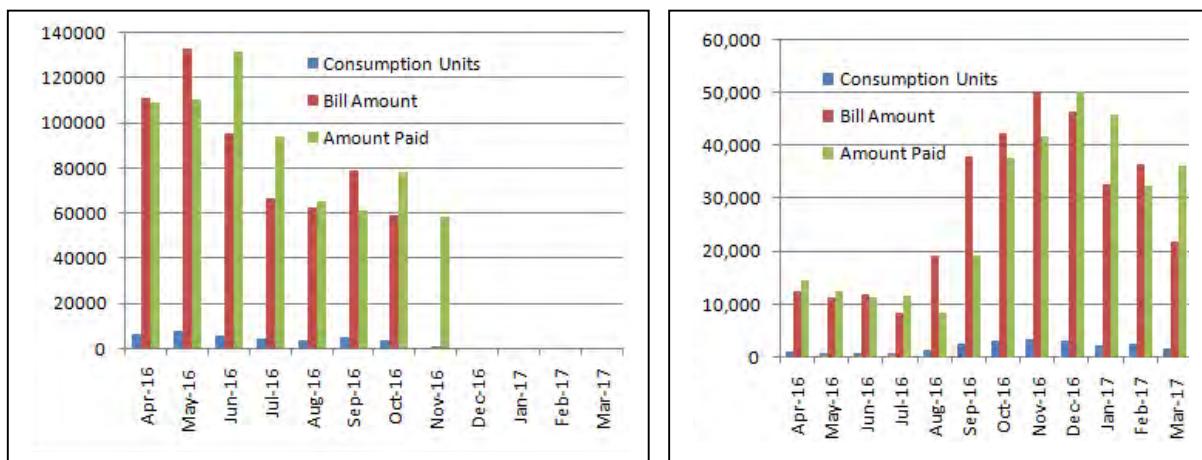


Figure 2. Graph showing Electricity consumption scenario of Nandan Prospera on left and Guruprasad on right

### **Data Collected for Padmavati Housing Community(PHC)**

Table 3 History for Electricity Consumption for PHC pre and post SRTPV installation done in Oct 2016

Bill Month	Consumption Units	Bill Amount	Amount Paid
Apr-17	964	6,570.00	0
Mar-17	0	-4,210.00	8,270.00
Feb-17	392	3,770.00	4,330.00
Jan-17	411	4,330.00	6,590.00
Dec-16	596	6,590.00	7,460.00
Nov-16	678	7,460.00	12,770.00
Oct-16	3,209	12,770.00	27,660.00
Sep-16	2,020	27,660.00	20,660.00
Aug-16	1,595	20,660.00	31,930.00
Jul-16	2,309	31,930.00	31,140.00
Jun-16	2,157	31,140.00	39,910.00
May-16	2,634	39,910.00	30,530.00

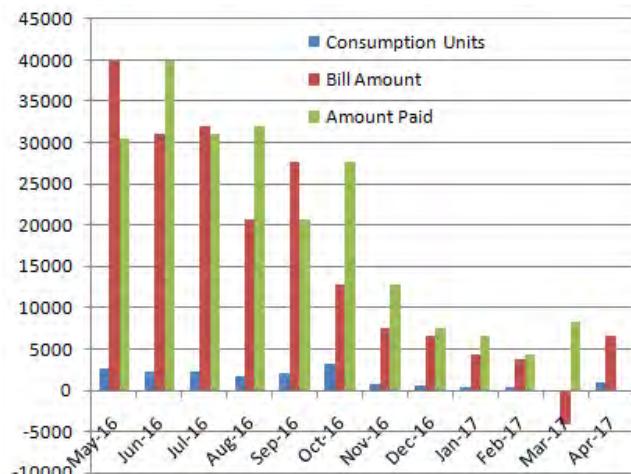


Figure 3.Graph showing Electricity consumption scenario of Padmavati Society

It should be noted that during the month of March 2017, there has been no usage of electricity from grid. Rather, the society has given units to the grid through net metering system and has gained in the electricity bill.

### **Findings**

The investigators selected 3 residential communities, each that had installed a Solar Roof Top PV System with authentic data of the electricity bills before and after the Solar Roof Top PV system installation. The analysis of the data shows the communities becoming self reliant and energy efficient owing to the installation of SRTPV systems. The benefits are in the form of reduced electricity bill. The tariff structure that is at Rs. 15/unit as per the state electricity bill is reduced to Rs. 9.5/unit after generating the energy by SRTPV. Although the question is of high installation cost of the system, the payback period is just under 4 years. The contributions of the residents for monthly maintenance expenses for the communities reduced and were nearly stabilised post SRTPV installations. **This proves hypothesis #H1.** The authors validated the findings by applying the concept to another residential community in Balewadi. The details of the calculations for the selected SAHIL SAGA community are presented.

SAHIL SAGA is one of the well known residential communities in Baner, Pune. It has 9 storey twin towers and 84 residential units, having common area lighting, two lifts per wing, swimming pool pumps and pumping station. The electricity consumption of the community is 5000 units in a month. 50% of the free area on the terrace is occupied by solar water heaters. Shadow free area of about 2500 sqft is available on terrace which is south-facing. Calculation with the given information for installation of SRTPV system is given forth.

In India, 300 sunny days are available. So apparently, we have 25 days a month to be utilised to generate 5000 units that are required monthly by the community. Daily, a generation of 200 units is required to suffice the monthly energy needs.

1Kwp solar system can generate 5 units of electricity in a day. So,  $200/5=40$  KWp system is needed for the provision of total energy consumption of common areas of community. The area available on the terrace is 2500 sqft which can accommodate a solar PV system of 25KWp. Installation of this capacity can achieve upto 85% reduction in electricity bill.

As per the maximum solar city mission for the pilot smart city area, 10% of total energy for any smart city needs to be generated through solar. In the present study of the community in the smart city area, 10% of the community's energy needs are being met on site by SRTPV. This is directly reducing transmission and distribution losses as well as reducing peak load demand of the grid. Wasteful of use of energy from the grid is mitigated as an outcome and is seen effectively contributing to efficient use of energy. **This proves hypothesis #H2.** During the investigations, it was also noted that there were few constraints that deterred the communities from installing Solar Roof Top PV system. They were found out to be as under:

*a. Orientation of the Structures*

Most buildings were not oriented in such a way that the East-South-West sunpath that gives maximum irradiation in India could be addressed by proper installation of panels.

*b. Architectural Design and Aesthetics*

The authors observed that many structure in the different communities studied over the course of research gave importance to aesthetics and elevation features of the buildings resulting into decorative staircase mumties and off-beat designed water tanks that led to scarce spaces for Solar PV panels installation. Also, these elements contributed to casting their shadows on favourable areas for Solar PV installations.

*c. Solar Water Heaters*

The provision of solar water heaters has been made mandatory for obtaining statutory building plan approval by the Urban Local Body in Pune where the study zone lies. Thus, most of the area on the terraces of the high rise buildings within the communities is occupied by solar water heaters leaving minimal area for Solar PV installations.

*d. Outlook of the residents*

Residents have many doubts regarding the working of the system for the community, not due to its output, but due to the high initial cost of installation and maintenance required later.

## Conclusion

While all the data and its analysis stand for SRTPV installations as a means of achieving energy efficient communities, it can be concluded that:

- a. There needs to be a widespread propagation of the system among not only residential communities, but also among institutional, educational and industrial communities to achieve energy efficient cities at large.
- b. Passive techniques of harnessing solar energy such as architectural designs, elevation features of buildings, orientation of south facing structures (specific to Indian conditions) should be considered while planning the layout of the communities.
- c. Solar water heaters are an extremely welcome step as they save electricity required for operating geysers. As they consume terrace spaces, their design and installation should also be meticulously done to leave space for Solar PV panels.
- d. Just as the solar water heaters have been made mandatory for building plan approval process in Pune, likewise, the urban local bodies across India should make Solar PV system mandatory for structures and encourage the captive generation of electricity.
- e. Another way of mitigating this issue can be the use of Building Integrated Photo Voltaic (BIPV) systems that can be installed on building surfaces-Vertical surfaces like walls, windows, sun breakers, slanting surfaces like roofs, weather sheds, horizontal surfaces like parking sheds, corridor roofs, porches etc. Design innovations can be done to have a solar panel inclusive design.
- f. Many innovations have been done to make use of solar panels for paving and other construction elements. These can be used in the communities.
- g. Building & Community Developers and real estate companies should propagate use of BIPV and other solar power harnessing materials alike.
- h. People need to be made aware about the use of SRTPV towards energy efficiency, propagating green buildings and mitigating climate change. They need to be convinced about the positive outcomes of the system in saving a lot of latent and incomprehensible financial cost against initial installation cost of the system.

### **Investigation's Impact**

The authors proceeded with the study to prove out there is a lot of scope for the installation of SRTPV and make efficient use of energy, not only by generating it on site but also reducing the transmission and distribution losses. This is certainly a step towards making the communities efficient and sustainable.

### **References**

- [https://en.wikipedia.org/wiki/Efficient\\_energy\\_use](https://en.wikipedia.org/wiki/Efficient_energy_use) accessed on 12 April 2017 at 10.22 am.
- <http://www.iea.org/topics/energyefficiency/> accessed on 12 April 2017 at 10.25 am.
- <http://powermin.nic.in/en/content/overview-2> accessed on 12 April 2017 at 10.32 am.
- [http://solarrooftop.gov.in/Grid/financial\\_tool/2](http://solarrooftop.gov.in/Grid/financial_tool/2)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Relevance of architectural design on the efficiency of district heating systems

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**Abstract:** At the global level, district energy systems have been used at different scales; Complete cities; University campuses and at the level of autonomous neighbourhoods, proving that district heating and cooling systems can optimize the use of energy of buildings by allowing to recycle heat which otherwise would be wasted or difficult to use. The question about the impact that the architectural and urban design has on these systems arises, since the energy performance of a building is dependent of the adequate architectural design. The main results of this review show that architects designing should work together with engineers early on the design process to define the main aspects of the district heating system, by means of a heating and cooling master plan that defines relevant parameters such as proportion of glazing and orientation, space for the installation of solar heating and photovoltaics panels and thermal mass of the buildings. The use of thermal mass to match energy demand with the availability of solar energy is a topic identified that leads to further research as being able to take advantage of solar energy and solar gains seems to be very relevant to the efficiency of the system.

**Keywords:** district heating, urban planning, energy efficient architecture, energy sources, design parameters.

### Introduction

When signing the agreement at the Paris climate conference (COP21), a large number of countries in the world united to fight climate change. This means that the 133 signing countries (United Nations Framework Convention on Climate Change, 2016) commit to further developing policies on climate change as well as progress towards the achievement of sustainable development objectives. This objective is achievable by reducing the dependence on fossil fuels and at the same time assuring energy security. In this framework the need for more efficient and less contaminating energy and heat supply systems is clear.

Moreover the EU Commission “adopted in 2011 the Roadmap for moving to a competitive low carbon economy in 2050, focusing on the Energy Efficiency” (European Parliament, 2012, p. 2). In this scenario, District heating systems can contribute; using renewable energy sources; recovering heat from other sources; and using energy sources matching with local availability, all of which should result in less CO<sub>2</sub> eq generation.

### Research objectives and approach

The main objective is to know and evaluate the incidence of architectural and urban variables on the efficiency of District Heating systems. This knowledge will help make design decisions when planning new neighborhoods or designing a new building that would be connected to such systems. The intention behind this study is to demonstrate that indoor comfort, energy efficiency and a reduction in greenhouse gasses is achievable when working

on a triad that includes urban fabric design, architectural design and centralized heating systems.

This paper presents the first approach to District heating, focusing on the definition of different technologies and the current development in the field. It revises the urban and architectural decisions that affect the efficiency of such systems, and finally sets the foundation for further research.

### **District Heating**

District heating systems aim to use local fuel or existing heat sources that otherwise would not be exploited to deliver heat and hot water to residential, commercial or even industrial customers through a distribution network at competitive prices with less pollution than traditional heat sources. This technology exist since the 14<sup>th</sup> century (Rezaie and Rosen, 2012), but their modern use arouse at the beginning of the 20<sup>th</sup> century to deal with hygienic and risk issues related to the use of wood burning and coal stoves in densely populated areas of big cities both in USA and Europe. Former individual heating systems where polluting the air, generating risk of fire and could not deliver proper internal heating conditions.

The main improvements that District Heating (DH) systems could offer where; the decrease in fire hazard superseding open flame coal or wood burners inside buildings, the reduction of the risk of burst boilers since the equipment was centralized, reduction of smoke nuisance and prevention of damage to the surfaces of the buildings. The production of pollutants was also diminished by using air filters. But the most relevant improvement for the indoor conditions and therefore for the users, were the uniformity of temperatures and absence of dust or pollutants both related with indoor comfort (Gallo, 2003).

Other side improvements of DH at an urban scale are the decrement in the transport of fuel and on a building level and more available space for architects and developers to profit from. For example the use of basements to accommodate luxurious restaurants, stores and others in New York (Willis, 1995).

A district heating system is composed of four main components; heat production plant, distribution network, customer substation and internal distribution system (Figure 1). The heat production plant is in many cases formed of several plants with different energy sources that converge in one system. The distribution network consists of two lines of pipes buried in the ground, one forwarding heat and the other returning the heat carrier at a lower temperature. Today the new systems use prefabricated steel pipes with polyurethane foam as insulation. The costumer substation is where both district and internal systems interconnect and exchange heat or water depending on the connection system. Typically the heat is transferred through heat exchangers called closed connection, but sometimes hot domestic water is prepared by mixing hot district water and cold water in an open connection as the method used in Russia (Werner, 2004). The internal distribution system is formed by at least two systems, one supplying heat to radiators and other to domestic hot water, a third system could heat supply air in mechanical ventilation systems.

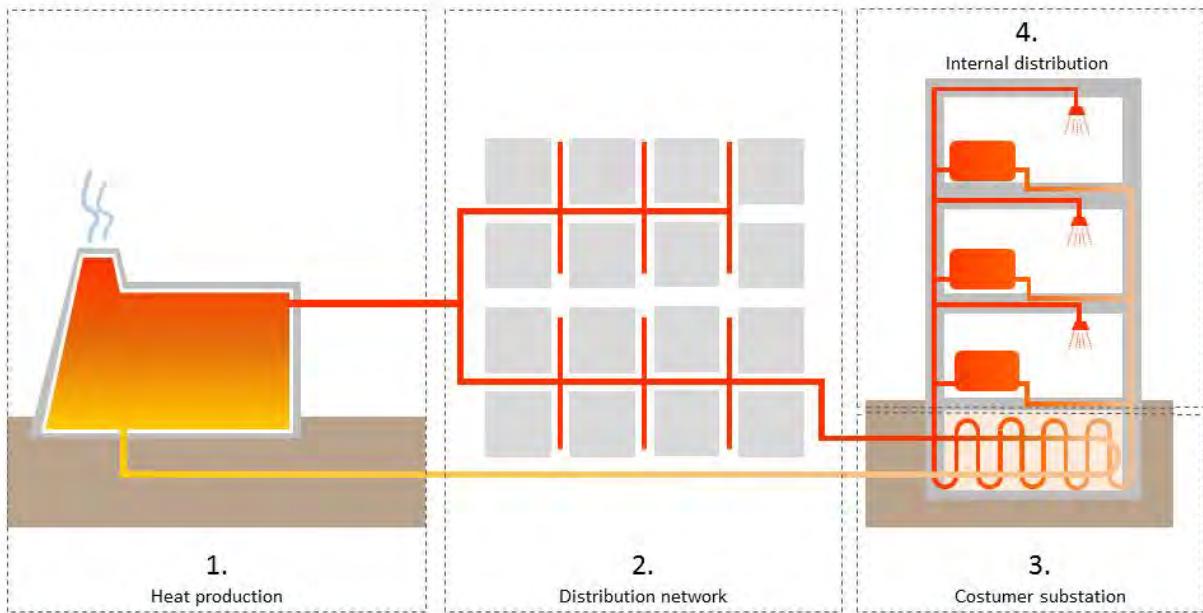


Figure 1: Components of a district heating system

The history of District heating systems recognizes four generations as described on Table 1 based on Lund et al. (2014). The technological advancement focuses on two key aspects, heat carrier and energy source. The characterization of a system should consider at least three factors; heat transport fluid, aim of the service and heat resource. Transport fluid could be vapor, water and air, being water the most used today. The aim of the service could be heating, cooling or both integrated in a single system. The heat source will be discussed in the following point.

These four generations show that the technological development of the systems was closely related with the security of supply and the losses in distribution. Steam had high losses in distribution and was prone to steam explosions. The change to pressurized hot water diminished both losses and burst, but the second generation was unable to control heat demand. The third generation, known as the “Scandinavian district heating technology” uses prefabricated buried pipes and substations to control heat demand. The fourth generation focuses on the integration of renewable energy sources and delivering low temperature water heating to energy efficient buildings.

Other field that has had changes in the last years is energy sources. In the beginning oil, gas and coal where the preferred energetics, nowadays the only country that still uses coal as main source of heat is China. European countries started to shift to other sources, being Sweden one of the leaders, increasing the use of biomass since the oil crisis in 1973 (Lake, Rezaie and Beyerlein, 2017).

Table 1: evolution of district heating systems

	1 <sup>st</sup> Generation	2 <sup>nd</sup> Generation	3 <sup>rd</sup> Generation	4 <sup>th</sup> Generation
Period	1880 - 1930	1930 - 1980	1980 - 2020	2020 - 2050
Aim	Comfort, reduce risk of fire, air quality	Fuel savings and reduced costs	Security of supply	SES <sup>1</sup> and integration with other systems
Heat carrier	Steam	Pressurized hot water mostly over 100 °C	Pressurized hot water mostly below 100 °C	Low temperature water between 30-70 °C
Heat Production	Steam boilers	CHP, heat only	Large scale CHP	Heat recycling
Main Energy source	Coal	Coal and Oil	Biomass, waste and fossil fuels	Surplus heat and energy, renewable sources
Buildings	Apartment and service sector buildings in the city	Apartment and service sector buildings	Ap. and service sector buildings and some single-family houses	New energy efficient buildings
Energy demand of buildings	--	200-300 kWh/m <sup>2</sup>	200-300 kWh/m <sup>2</sup>	Less than 25 kWh/m <sup>2</sup> for new and 50-150 kWh/m <sup>2</sup> for existing buildings
Emitters	High-temperature radiators (+90 °C) using steam or water.	High-temperature radiators (90 °C) using water directly or indirectly.	Medium-temperature radiators (70 °C) using water directly or indirectly or floor heating	Low-temperature radiators or Floor heating. (50°C). Indirect system
Cities	Paris (1927) New York (1882)	Iceland geothermal DH (1930)	Stockholm, Copenhagen, others	--

## Energy Sources

The first district heating systems in USA used coal as their main energetic, further development allowed to use the remaining heat from the production of electricity in combined heat and power (CHP) plants. The selection of energy resources is mainly related with availability and technology, nowadays this selection is shifting to environmental issues mainly production of CO<sub>2</sub> eq and exergy. The following list shows the main energy sources in use or development.

**Fossil fuels:** Fuels like natural gas, petrol, coal, oil can produce energy and heat. Their main advantage is that they are currently in use and the ease to control the amount of energy or heat produced according to the specific needs. They are a big source of greenhouse emissions, are not renewable and have very high exergy. Existing HD are shifting to renewable sources.

**Waste to heat or waste incineration:** Domestic waste is incinerated to generate heat or heat and electric energy (CHP). This technology reduces the amount of garbage that goes to landfills while providing heat and power. The fumes from the process are potentially harmful and need a proper management to prevent health related problems, the proportion of ashes to waste in kg is around 3% in the case of Malmo (SYSAV, 2012). Waste to heat technology was first used in the Nordic countries where Sweden had a leading role, using nowadays, all their domestic waste as heat source.

<sup>1</sup> Sustainable Energy Systems

**Geothermal:** used in locations with geothermal sources like hot springs or geysers. They provide low cost heating through district heating. It is not always available and the cooling of underground water reservoirs should be considered.

**Biomass:** Wood or crops are used as fuel considering them as carbon-dioxide neutral and therefore an environmentally responsible alternative. There could be an issue with the displacement of crops for human consumption and proper management to ensure CO<sub>2</sub> neutrality. Waste from forestry management is commonly used.'

**Combined Heat and power:** or cogeneration is the technology that allows to produce electrical power and at the same time heat from the same source. The generation of heat as a byproduct of power generation increases the efficiency of the process. The fuel could be any of the above mentioned.

**Waste heat:** Uses the waste heat produced by other industries or buildings to generate hot water. If the source is far from the heating area losses could be too high. Current research on 4<sup>th</sup> generation DH proposes the use of heat from cooling in commercial buildings to heat other buildings (Lund *et al.*, 2014).

**Solar-thermal:** Solar collectors can heat water for heating and cooling purposes (absorption chillers). Solar radiation has greater availability in summer when heating is not needed so that demand will not always coincide with availability; therefore heat storage could be needed.

**Surplus electricity (wind or solar):** Current research shows that using energy surplus to heat water together with heat storage could avoid critical electricity-production (Lund and Münster, 2003) and give security to the network.

The future goal is utilizing low exergy energetics from renewable sources. The integration of district heating with smart energy systems will also allow using the surplus energy produced from solar or wind electricity for heating or cooling. Although the exergy of this process is high, the main intention is to give security to the energy supply and protect it from peaks in production. Nowadays existing DH systems integrate heat storage to integrate seasonal heat sources (Nielsen and Möller, 2012)

### Urban planning for district heating systems

When analysing the costs of a new DH system, the main investment goes to the heat production and distribution network. A dense urban area will need a shorter distribution network than a spread one, this also means that more buildings will be connected to the system. Linear heat density; meaning the heat sold divided by the length of the pipes in the distribution network, is the indicator to evaluate the cost effectiveness of the system.

According to Werner (2004, p. 844) 'Typical values for linear densities are 15-25 GJ/m for whole networks, more than 40 GJ/m concentrated downtown and commercial areas, and less than 5 GJ/m in blocks with single family houses'. The smaller linear density, the greater the distribution cost. Linear density will be affected by several factors such as urban dispersion or centralization, size of buildings, vertical density and typology of buildings. These factors will determinate if it is feasible to implement a DH or not (Persson and Werner, 2011).

**Density:** Density is relevant in the dispersion of units in the cities and relevant factor when deciding if a DH project is viable, because the amount of heat losses due to distribution will be less relevant when pondered by surface heated (Wiltshire, 2011). High rise buildings will allow having more dense areas.

**Climate:** The heating or cooling season will depend on climate conditions. Milder climates will need less heat power, and will need heating for less time per year.

### **Architectural design for district heating systems**

As stated in (Stennikov and Iakimetc, 2016) energy efficient buildings will reduce heat consumption, which will change the heat density map and should shape or reshape the energy plan of cities. These changes in buildings can also affect the period of heating and cooling and the peaks in consumption of heat and cooling load. The design of the heat supply should be defined in the initial phase; therefore it is relevant to know in advance the energy quality of the future buildings. Wiltshire (2011) explains that energy efficient buildings will decrease energy requirements for heating which will make domestic hot water supply (DHW) the main requirement. This will also flatten the annual heat profile, reducing the heat load in winter. This means that the production of hot water will remain seasonal but the difference between winter and summer requirements will decrease.

The decrease in energy demand will propitiate the use of low temperature DH (Persson and Werner, 2011) as is the case of 4<sup>th</sup> generation district heating, while current research is focusing on this aspect.

Other factors that are related with the delivery of heat through radiators or radiative surfaces is high thermal mass as a regulation system that will help maintain indoor comfort when the border conditions change, like external temperature or alternative use of heat for DHW (Li and Wang, 2015). Thermal mass can also shift the peak in demand to periods during the day when more heat is available, this is especially relevant when peaks in heating and DHW coincide.

Another strategy to manage peak heat requirements and local ability is mix-use buildings. This buildings could combine dwellings with heating requirements with other uses that produce heat as servers (Stockholm Data parks, 2016).

### **Integrated design**

Connolly et al., proposes that district heating is crucial to the implementation of future sustainable energy systems (2014). But to achieve such ambitious goals low temperature district heating should be implemented in coordination with low energy buildings. The design of energy efficient buildings should be part of energy efficient neighbourhoods. The renovation of existing buildings is also an issue that should be taking into account when designing new or renovated DH (Park and Andrews, 2004; Gartland, 2015).

### **Further research**

Future work on the relevance of architectural design on the efficiency of district heating systems should focus on detailed dynamic simulation of buildings to prove the effect of thermal mass and mixed-use building design to improve the efficiency of district heating systems.

Since district heating was developed for cold climates with long winters and dense urban areas, adapting it to other climates and urban settings should also be studied considering the benefits that such systems have on air quality and indoor comfort. Research should be focused on 4th generation developments considering the incorporation of renewable sources of heat into the system in non-industrialized countries.

## **Conclusions**

Spatial planning should consider the energy demand of existing and future buildings whereas they are going to be part of a district heating system or not, considering the heat demand density and the usage patterns of buildings. The feasibility of integration of renewable energy resources should also be considered.

It is relevant as well to plan for future scenarios considering expansion of the cities and renovation of buildings to new standards, always considering the future climate scenarios.

The district heating of the future should pay much attention to the energy sources to use, to lower the production of greenhouse gasses and diminish climate change. Environmentally responsible options are available from waste heat, geothermal, solar thermal to waste incineration. Each energy source should be evaluated for each case since technology and availability are a key aspect in lowering emissions. Waste incineration should be assessed considering the alternative use (landfill or other) to evaluate its impact.

Including surplus energy from renewable sources could help ensure energy security and should be addressed in an integrated manner with electricity production.

As stated by Persson and Werner (2011, p. 568) 'The competitiveness of present and future district heating systems can be at risk when residential and service sector heat demands are expected to decrease in the future', Therefore architects and urban planners have to consider the evolution of DH.

It is relevant to state that District Heating system where developed in cities with a dense urban fabric in southern latitudes with cold climates. The adaption of these technologies in other contexts needs to be done considering the adaptation to the local context which in this case includes: climate, urban, construction technologies, governance, social and cultural aspects. This paper presents some highlights of the urban, construction technologies and design aspects that should be considered when designing in other climates with district heating systems in mind.

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## **References**

- Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P. A. and Nielsen, S. (2014) 'Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system', *Energy Policy*. Elsevier, 65, pp. 475–489. doi: 10.1016/j.enpol.2013.10.035.
- European Parliament (2012) 'Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency', *Official Journal of the European Union Directive*, (October), pp. 1–56. doi: 10.3000/19770677.L\_2012.315.eng.
- Gallo, E. (2003) 'Skyscrapers and District Heating , an inter-related History 1876-1933', *Construction History*, 19(19), pp. 87–106.
- Gartland, D. (2015) 'Dublin City Spatial Energy Demand Analysis'. Available at: <http://www.codema.ie/images/uploads/docs/>.
- Lake, A., Rezaie, B. and Beyerlein, S. (2017) 'Review of district heating and cooling systems for a sustainable future', *Renewable and Sustainable Energy Reviews*. Elsevier, 67, pp. 417–425. doi: 10.1016/j.rser.2016.09.061.
- Li, H. and Wang, S. J. (2015) 'Load Management in District Heating Operation', *Energy Procedia*. Elsevier B.V., 75, pp. 1202–1207. doi: 10.1016/j.egypro.2015.07.155.

- Lund, H. and Münster, E. (2003) 'Management of surplus electricity-production from a fluctuating renewable-energy source', *Applied Energy*, 76(1–3), pp. 65–74.
- Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F. and Mathiesen, B. V. (2014) '4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.', *Energy*. Elsevier Ltd, 68, pp. 1–11. doi: 10.1016/j.energy.2014.02.089.
- Nielsen, S. and Möller, B. (2012) 'Excess heat production of future net zero energy buildings within district heating areas in Denmark', *Energy*. Elsevier Ltd, 48(1), pp. 23–31.
- Park, H. and Andrews, C. (2004) 'City Planning and Energy Use', *Encyclopedia of Energy*, 1, pp. 317–330. doi: <http://dx.doi.org/10.1016/B0-12-176480-X/00498-8>.
- Persson, U. and Werner, S. (2011) 'Heat distribution and the future competitiveness of district heating', *Applied Energy*. Elsevier Ltd, 88(3), pp. 568–576.
- Rezaie, B. and Rosen, M. A. (2012) 'District heating and cooling: Review of technology and potential enhancements', *Applied Energy*, 93, pp. 2–10. doi: 10.1016/j.apenergy.2011.04.020.
- Stennikov, V. A. and Iakimetc, E. E. (2016) 'Optimal planning of heat supply systems in urban areas', *Energy*. Elsevier Ltd, 110, pp. 157–165. doi: 10.1016/j.energy.2016.02.060.
- Stockholm Data parks (2016) *Data Center Cooling with Heat Recovery*.
- SYSAV (2012) *Heat and electricity from waste: Sysavs waste to energy plant in Malmö*. Malmö.
- United Nations Framework Convention on Climate Change (2016) *Paris Agreement - Status of Ratification*. Available at: [http://unfccc.int/paris\\_agreement/items/9444.php](http://unfccc.int/paris_agreement/items/9444.php).
- Werner, S. (2004) 'District Heating and Cooling', *Encyclopedia of energy*, pp. 841–848.
- Willis, C. (1995) *Form follows finance: Skyscrapers and Skylines in New York and Chicago*. New York: Princeton Architectural Press.
- Wiltshire, R. (2011) 'Low Temperature District Energy Systems', in *Proc. of 17th Building Services, Mechanical and Building Industry Days, Urban Energy Conference*, pp. 13–14. Available at: <http://aaltopro2.aalto.fi/projects>.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Conceptual Framework for Optimal Urban Energy Planning Tool with an Intelligent System through Integration of BIM and GIS Technology

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**Abstract:** Sustainable urban energy system planning on an urban scale is becoming increasingly more important for urban developers. To realize energy conservation in urban areas, various policies or technologies that should be integrated should be determined based on demand-side information on building features and their utilization conditions, as well as on the energy supply infrastructure and local renewable energy resource potential. However, the existing energy planning tools that focus on individual energy conservation technologies do not easily support such comprehensive planning. One of the obstacles is unifying the urban Big Data from different sectors, which is difficult to achieve without an intelligent system. To overcome this problem, in this paper we propose a conceptual framework for an urban energy planning tool with an intelligent and autonomous system that integrates building information modelling (BIM) and a geographic information system (GIS) based on the previous work (Yamamura, 2016). We first introduce the concept and architecture of the tool. The applicability of the tool is then examined by applying it to a Japanese city center. Finally, environmental effects are evaluated to achieve an optimal energy system with a combination of multiple technologies and networks for the district studied.

**Keywords:** urban energy planning, building information modelling (BIM), geographic information system (GIS) technology, renewable energy utilization, district cooling and heating

### Introduction

Urban agglomerations are continuing to grow on a global scale. Despite being conducive to economic growth, they cause many problems. Currently, cities already use about 75% of all global energy resources and emit 70% of global greenhouse gases (Beuzekom, 2015). With rapidly growing, denser populations, cities have been suffering from chronic traffic congestion and frequent power failures due to a constant energy shortage, both of which make life difficult for inhabitants and cause significant loss of economic opportunity. To resolve the situation, city administrations need to promote multifaceted urban infrastructure development along with urbanization, which encompasses roads, public transportation, water supply and sewage, the energy supply system, and demand information.

From this perspective, our previous research proposes an architecture for a comprehensive smart city planning aided tools (Yamamura, 2016) that considers all the information from the above sectors. Urban energy planning tools is the most important part that need to be firstly development. Various policies or technologies should be comprehensively considered based on demand-side information on building features and

their utilization conditions, as well as on the energy supply infrastructure and local renewable energy resource potential. In other words, the urban energy planning system should be a tool that can achieve an optimal approach, with synergies among the various elements in the urban planning process and ultimate energy solution.

Most of the existing energy planning tools focus on energy conservation technologies in one or several buildings, which are difficult to apply to energy planning on an urban scale. Existing research gives an overview of these energy planning tools (van Beuzekom, 2015), in addition to identifying two important challenges of such tools. One challenge is the lack of consideration of energy infrastructure, such as electricity networks and gas pipelines. The other is the low renewable energy utilization on the urban scale. Some researchers have begun to focus on urban energy planning systems and have developed a system that can estimate the potential of renewable energy on a city scale using geographic information system (GIS) technology. However, it has not yet been combined with the existing building energy system (Yeo, 2014).

According to prior analyses, the existing energy planning tools cannot easily support such comprehensive planning. One of the difficulties for such tools is unification of the urban Big Data from different sectors, which is difficult to achieve without an intelligent system. Another difficulty is in the visualization of related factors, which makes the analysis and understanding of the information on urban infrastructure, urban planning, renewable energy, and untapped energy easier.

To overcome these problems, as the sub-tool for the smart city planning tool that proposed in the previous research, in this paper we propose a conceptual framework for an urban energy planning tool with an intelligent and autonomous system using the integration of building information modelling (BIM) and GIS technology. In the research reported herein, the data of energy elements and related urban infrastructure are unified by a three-dimensional (3D) city model in a GIS. BIM focuses on the building scale, describing the buildings in a geometric manner with detailed information on the buildings, energy system, and related facilities. All such urban Big Data on different scales and from different sectors is visually integrated by the GIS-BIM platform, while the analysis and simulation process is integrated by the intelligent and autonomous system.

We first introduce the concept and architecture of the tool. The applicability of the resulting model is then examined by applying it to a Japanese city centre. Finally, the environmental effects are evaluated to achieve an optimal energy system through a combination of multiple technologies and networks for the district studied.

## **Concept and architecture of proposed tool**

### ***Overall concept***

In the previous research, we have proposed the concept and architecture of smart city aided planning tool. As we mentioned, it is a complex system related to weather information, transportation, energy information, facilities, and city infrastructure (Figure 1) in planning and simulation processes, providing supportive technology that can perform the following functions:

- (a) Modelling of the actual urban space in cyber-physical space, including building information, urban planning information, energy supply and demand information, and renewable and untapped energy information.

- (b) Setting up of scenarios with various technologies to facilitate analysis and discovery of optimal site locations of an urban energy system within the cyber-physical space.
- (c) Evaluation and visualization of the system's ability to realize an optimal urban energy solution.

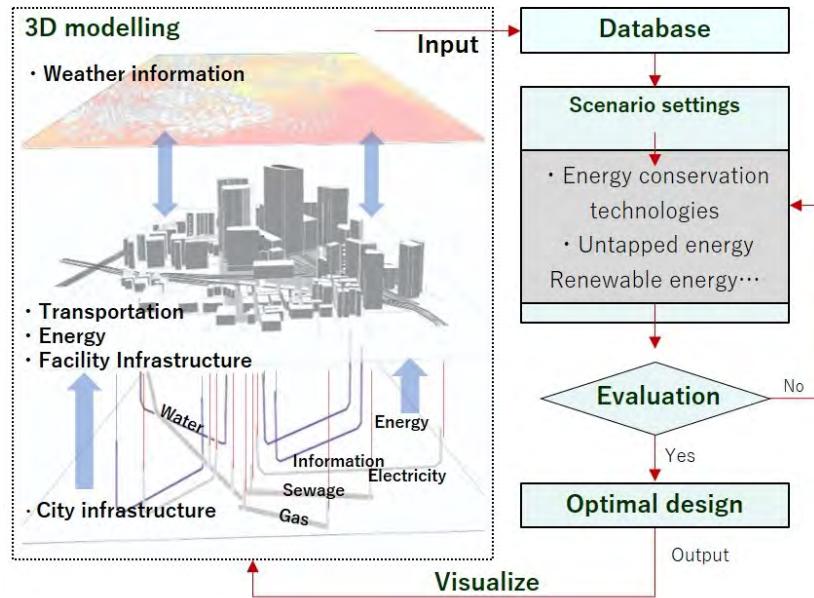


Figure 1. 3D model of the city and flowchart of the concepts underlying the tool's function

## Architecture

To address the above issues, in this paper we propose a GIS-BIM-based system that can simplify building Big Data sets from BIM and integrate it with the city model built by the GIS. This system consists of two parts: database and platform (Figure 2).

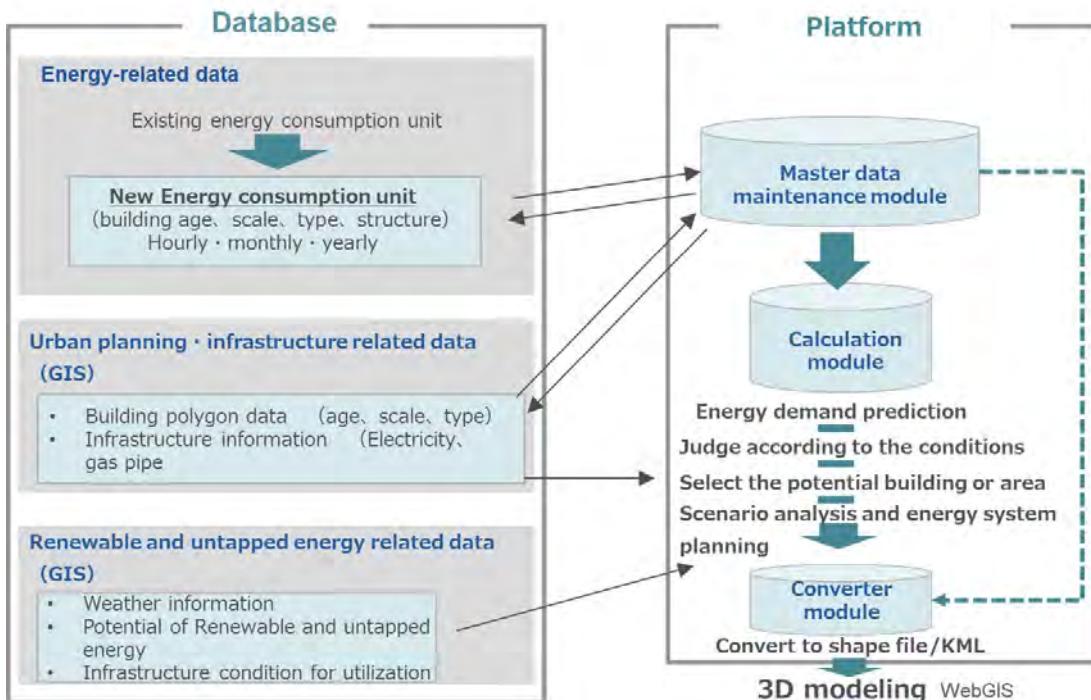


Figure 2. Architecture of the proposed tool

The database component interprets the city using layered data. The building information related to energy consumption is from the BIM process, and the other urban infrastructure data are from GIS. In the research reported herein, the database is comprised

of three main parts. The first comprises the data of energy consumption information used in estimating the city's existing and predicting its future energy consumption. The energy consumption data for different types of buildings are presented as annual, monthly, and hourly energy consumption units (energy consumption per square meter) based on a survey, which is described in the following paper. The buildings are categorized by their year of construction, scale, type, structure, and the urban planning information from GIS data. The second part comprises the data related to urban planning and infrastructure. This part is supported by the GIS, including building polygon data (with information on year of construction, building area, and building type) and infrastructure data (such as power lines and gas piping). The third part comprises the database for renewable and untapped energy, which is also supported by the GIS, and it is used in estimating the potential of renewable and untapped energy.

The platform component is the main part of the tool, containing the functions for achieving an urban energy solution through visualization, simulation, and evaluation. It is composed of three modules: the master data maintenance module, calculation module, and converter module. The master data maintenance module is responsible for adding, deleting, and modifying the data in the database component, and import the datasets from the BIM-GIS system to the database component. The calculation module uses the data from the database to predict the energy consumption, to find an optimal site location for an urban energy system based on a given scenario, and to simulate and evaluate the system to achieve an optimal design. The converter module is used for visualization. It converts the simulation results and visualizes them by the 3D supportive technologies in the GIS-BIM system.

### **Process**

Urban energy planning using the proposed tool should adhere to the following process:

1. The building information is obtained from the urban planning database via the master data maintenance module and input it into the database component;
2. The calculation module selects the energy consumption data according to the building information from the database component;
3. The calculation module predicts the urban energy consumption using the energy consumption data and building information from the database component (Steps 1 and 2);
4. The urban infrastructure data are loaded to facilitate evaluating the possibility of an urban energy supply plant;
5. The information is obtained and the potential of renewable and untapped energy is estimated by the calculation module;
6. An optimal site location for the system is found according to Steps 3–5;
7. Scenarios are established to simulate and evaluate the system for an optimal design;
8. The result derived from Step 7 is converted and visualized by converter module.

### **Applicability of the tool for urban energy system planning**

#### **Target area**

A Japanese urban center district was adopted for a case study to examine the applicability of the proposed model. GIS polygon data for urban planning, including building type, building area, and other information were acquired (Figure 3). The data suggest that this area has four

main types of building and most of them are commercial and office buildings. More than half of the buildings are large-scale buildings<sup>1</sup>.

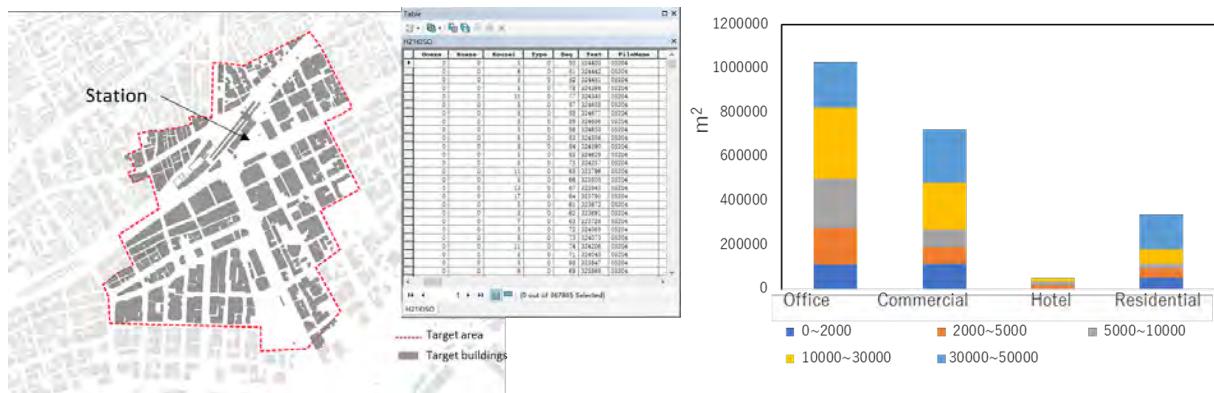


Figure 3. Target area of case study

### **Database construction**

The concept underlying the research presented in this paper was to provide supportive technology when searching for an optimal site location of an urban energy system in the planning stage of such systems. Proposed is a model with a site location and optimal design based on the site information, building features, energy consumption, and on-site renewable and untapped energy. Therefore, the database constructed to facilitate such goals consist of urban planning information acquired by a GIS, including building features and city infrastructure, as well as urban space information from BIM, such as underground shopping centers. Energy consumption data are estimated based on the building information and energy consumption units. See Figure 4 for representative views of database content.

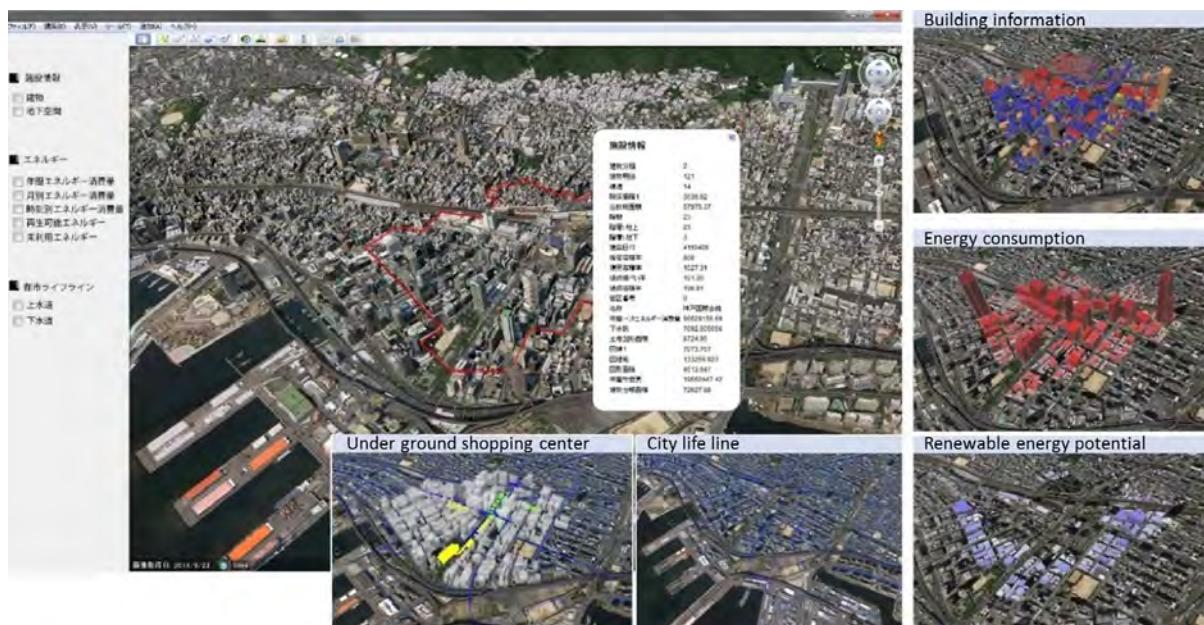


Figure 4. Images of database content

<sup>1</sup> Large scale is defined as a building area of more than 10,000 m<sup>2</sup>

### *Energy consumption*

The estimation of energy consumption uses yearly energy consumption units, the yearly energy consumption of every building type expressed in per unit ( $\text{m}^2$ ) (open database, DECC) and is calculated with the same method that in previous research (Yamamura, 2016), as follows:

$$\sum_i(\text{building energy consumption}) = \sum_i E_i \times S_i,$$

Where  $i$  denotes building type,  $E_i$  the yearly energy consumption for building type  $i$ , and  $S_i$  the building area for building type  $i$ .

Energy consumption units used in this paper are listed in Table 1.

Table 1 Yearly energy consumption units for different types of buildings

Type	Yearly energy consumption units (MJ/m <sup>2</sup> ·Year)
Commercial	4529
Office	1648
Mixed use	1600
Residential	778
Manufactory	1297

Through the 3D modelling executed by the tool, the energy demand distribution in the district is available (Figure 5). The modelling suggests that the buildings around the train station in the city center, for example, have higher energy consumption.

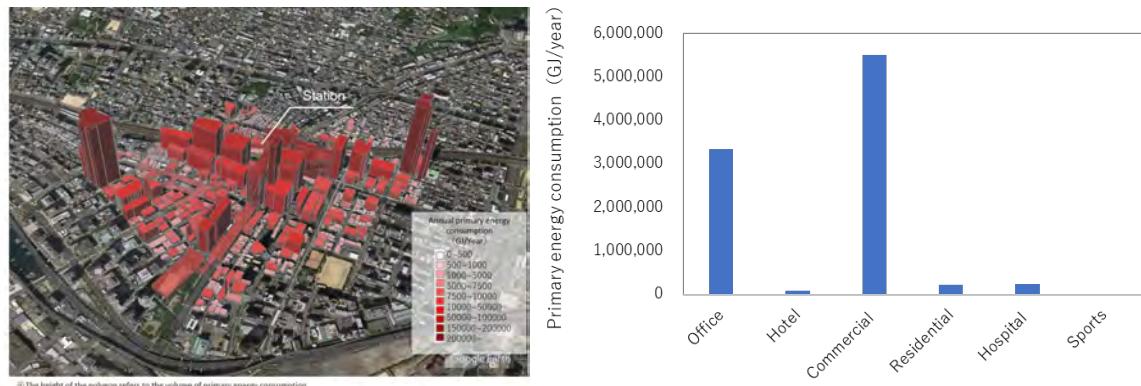


Figure 5. Primary energy consumption modelled in three dimensions by the tool

### *Renewable and untapped energy*

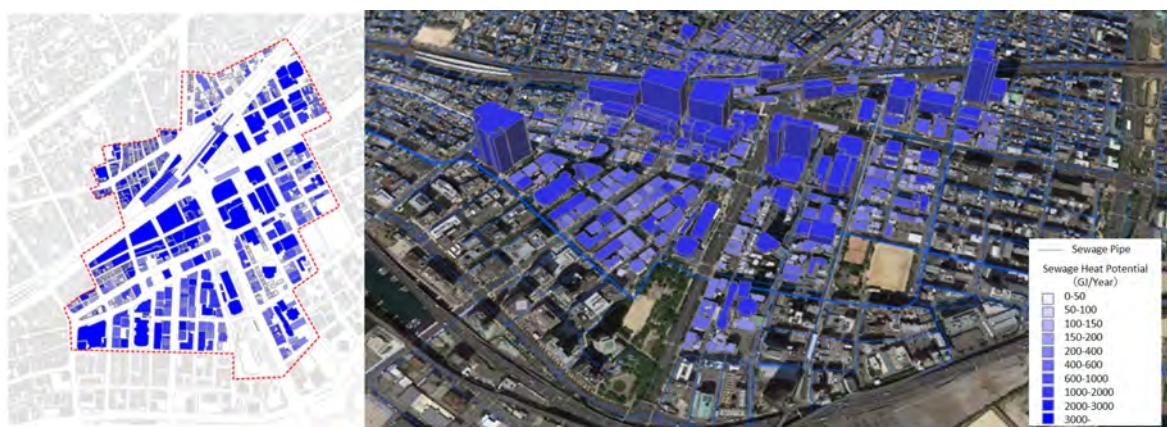


Figure 6. Renewable and untapped energy potential according to building area and sewage flow

The waste heat from sewage water is a form of untapped energy found in urban areas. Compared to the air temperature, it has a lower temperature in the summer and a higher temperature in the winter. The gap in temperature between sewage water and the air is estimated to average approximately 5°C. The heat potential can be estimated according to the building area and sewage flow, as suggested in Figure 6. Renewable and untapped energy potential

### Scenario analysis

The target area is an urban center with high energy consumption and electricity use at peak load. A district cooling and heating (DHC) system with a co-generation system (CGS) is planned to be introduced into this area for managing electricity peak cuts. Using the tool proposed in this paper, the information from different sectors of the target area, including urban planning, energy consumption, and renewable and untapped energy, can be unified by 3D modelling.

One of the challenges for introducing a DHC system in urban areas is the limited urban space for the required infrastructure, such as that needed for heat sharing between the target buildings. To meet this challenge, the proposed tool selects the areas for introduction of a CGS based on the following conditions:

- Buildings with high primary energy consumption and electricity peak load (which is available in the energy consumption unit as mentioned before);
- Buildings of large scale (a building area of more than 10,000 m<sup>2</sup>);
- Buildings with high untapped energy utilization potential;
- Areas with a building reconstruction plan;
- Areas that are connected by underground spaces, such as for underground shopping center (where the pipes for heat sharing would be situated).

Finally, three areas were selected as target areas.

The capacity of gas-fired power generators is set by the proposed tool as Figure 7 shows; this research established two cases to determine the effect of heat sharing between buildings, as follows:

Case 1: As in Figure 7(a), three areas into which individual CGS systems were introduced and the heat was not shared.

Case 2: As in Figure 7(b), three areas into which individual CGS systems were introduced and the heat was shared.

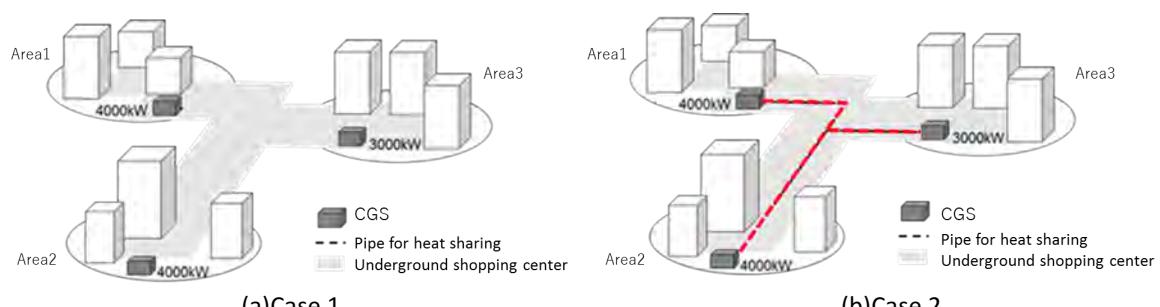


Figure 7. Cases established to study heat sharing using the proposed tool

The results suggest that, with the heat shared between the target areas (Case 2), the efficiency of the energy recovery rate is 5% higher than for the case in which no heat was shared (Case1).

## **Discussion and conclusions**

The research presented in this paper is based on a concept introduced in previous research (Yamamura, 2016). Based on the aforementioned concept, we developed a conceptual framework for integrating BIM and GIS technology in an intelligent system for complex urban energy system planning. The effectiveness of our proposed system was illustrated by conducting case studies using a Japanese city center, and it was found that with such an intelligent system as that proposed herein, the system can achieve the following:

- Combination, analysis, and visualization of the data from urban planning, energy information, infrastructure transportation, and other data resources across the level of a city or community, or even for individual buildings;
- Prediction and simulation of energy consumption and renewable energy potential;
- Provision of supportive technology when searching for an optimal site location for an urban energy system in the planning stages of such systems;
- Simulation, analysis, and comparison of the effects of different energy conservation technologies, facilitating visualization and easy understanding of the system effects through easily understood 3D models.

This research presented herein offers a description of the architecture of the middleware required, as a first step, for GIS and BIM data integration, query, and visualization. In future research, more details of energy planning, including cost performance, should be considered in the design of such a system.

## **References**

- I. van Beuzekom; M. Gibescu; J. G. Slootweg, 2015 IEEE Eindhoven PowerTech, A review of multi-energy system planning and optimization tools for sustainable urban development
- I.Yeo, J.Yee, A proposal for a site location planning model of environmentally friendly urban energy supply plants using an environment and energy geographical information system (E-GIS) database (DB) and an artificial neural network (ANN), Applied Energy 119 (2014) 99–117
- Open data base, <http://www.jsbc.or.jp/decc/>
- S.Yamamura, Assessment of urban energy performance through integration of BIM and GIS for smart city planning, Procedia Engineering,2017



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Energy Performance Plan Analysis in a New Ecological City

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**Abstract:** Conforming to urban development needs, in accordance with ecological and low-carbon requirements, is the first priority of contemporary urban construction. At the first stages of planning a new town, energy planning and analysis, and establishing sustainable energy development strategies, are methods to reinforce the ideal of an ecological city. Therefore, to meet urban planning requirements, energy planning often requires determination of the energy consumption index, and knowledge of local energy demands and natural and social environments (to build a reasonable energy structure), adjusted through the evaluation, design, and optimization of the construction of ecological cities. This paper explores energy planning through an analysis of the application of energy sources in the planning of the eco-city of Jinan City.

**Keywords:** Energy Performance, Energy Analysis, New Ecological City, Scenario setting, energy-resource structure

### Introduction

An Eco-city is one in which energy consumption, pollution, and emissions rates are low, thereby saving energy and enhancing environmental protection. Currently, China is constructing a large number of new ecological cities to adapt the development of the city, economy, and population for an ecological purpose. At the beginning of planning a new town, it is important that energy planning is conducted and applied to ensure that the goal of building an ecological city is fully realized. In the design of the 'Xiuyuan river ecological zone' in Jinan City, China, the energy consumption analysis and optimization method is adopted to fulfil ecological goals.

### City profile

Jinan City is located in central Shandong Province, and the Xiuyuan river eco-city is located in the western area of the old Jinan city, with a total area of 23.75 km<sup>2</sup>, and planned floor area of 28,700,000 m<sup>2</sup>. The land is mostly undeveloped, and the river flows through the center of the eco-city.

### Research method

The demand for a green eco-city is forecast by the scenario analysis method, which is based on eco-city planning, research on energy consumption in existing buildings, and an understanding and analysis of energy consumption.

A scheme for renewable energy planning, based on an assessment of renewable energy resources such as solar energy, shallow geothermal energy, wind energy, and conventional coal and gas energy in the total land area, is proposed.

The viability of various renewable energy sources is investigated, based on an assessment of renewable energy that matched construction types with renewable energy source.

A type of renewable energy suitable for each area is also proposed; by making efficient and rational use of energy programs, renewable energy sources in the ecological demonstration area and the municipal energy supply combined bear the primary energy load in the region, suggesting a reasonable energy system and mode of operation.

### **Energy demand forecast**

The energy consumption of the region is divided into heating load, gas load, and power load. According to the regional energy demand, heating load includes industrial heating, domestic hot water use, and summer air condition. Gas load includes residential cooking, commercial cooking, industrial, direct combustion engine, and gas vehicles. Electricity load includes residential, public facilities, industry, business, and others.

### **Basic scenario settings**

According to the construction status and the requirements of China's policy standards, based on the buildings energy consumption standards in 1980, short- and long-term residential building constructions require energy-savings of 75% and 80%, new public buildings require energy-savings of 65%, and the status quo is to maintain buildings according to current research results. Recently, public-building commercial gas consumption has accounted for 60% of residential gas use, and long-term commercial gas consumption accounted for 100% of residential gas use. In the long-term, gas-vehicle gasification rate is also considered.

#### *Residential building energy consumption basic scenario*

Residential land construction is divided into three categories: residential, basic education, and community services. Among them, the basic scenario parameters include the performance parameters of short/long-term new-building thermal envelopes, indoor thermal envelopes (lighting, equipment, personnel), indoor environmental control parameters, heating and air conditioning system operation mode, and other parameters based on the "Shandong Province Residential Building Energy Efficiency Design Standards" (DBJ 14-037-2012) design. The conditions for maintaining the building energy consumption indicators were based on research of current conditions. The building heating time is 120 days, and the air conditioning period cooling time is 61 days.

The summer indoor temperature and humidity were set at 26 °C/60%, and the winter indoor temperature and humidity were set to 18 °C/40%. The room ventilation time was 1 hr. to meet typical user comfort requirements.

Basic educational buildings include primary and junior high schools, and the air conditioning system is open Monday to Friday with a running time of 08:00-12:00 and 14:00 -18:00. In community service facilities, the air conditioning system is constantly running, and the daily running time is set between 8:00-21:00.

#### *Public building terminal energy consumption basic scenario*

Public buildings include business offices, commercial buildings, municipal buildings, and other public facilities. The basic scenario parameters are consistent with those of residential buildings.

### *Energy consumption of industrial and municipal buildings*

Industrial facilities cover the food processing, logistics, and transport sectors. The total area of industrial land is 12.9 ha. As it is only office energy consumption and does not include the actual output value of industrial buildings, energy consumption indicators, in accordance with R&D office building energy consumption indicators, are only calculated.

Municipal buildings mainly include postal services and telecommunications, transportation, and environmental sanitation; their energy consumption is similar to that of community service facilities, so energy consumption targets were referenced from those of community service buildings.

### **Heating load**

The building area is calculated using the area to floor area ratio. The heating area covers 90% of the building area, a total of 25.83 million m<sup>2</sup>, and has a heating rate of 100%(see table 1). Simultaneity usage coefficient of heating load design is 0.7.

Table 1. All types of buildings and their heating areas and heating rates

Building type	Construction area (10 <sup>3</sup> m <sup>2</sup> )	Heating area (10 <sup>3</sup> m <sup>2</sup> )	Rate (%)
Residence	20,140	18,126	70.2
Office	2,010	1,809	7
Business	4,890	4,401	17
Culture and entertainment	420	378	1.5
Industry	1,110	1,000	3.9
Others	130	117	1
Total	28,700	25,830	100

The urban area of the eco-city accounted for 70% of the construction area, giving a total of 20.09 million m<sup>2</sup>. According to the "Urban Heating Pipe Network Design Specifications" (CJJ 34-2010), and the types of constructions in the region, a comprehensive cooling data would require 75 W/m<sup>2</sup>. Simultaneity usage coefficient of design heating load for air-conditioning is 0.7.

According to the "Urban Heating Pipe Network Design Specifications" (CJJ 34-2010), daily residential hot water use has a daily average heating load data of 12 W/m<sup>2</sup>. Other buildings has a daily hot water data of 10 W/m<sup>2</sup>, and hot water has a design load factor of 0.65.

Based on the above analysis, designed heating load of this city in short- and long-term can be calculated(see table 2).

Table 2. Designed heating load (10<sup>3</sup> kWh)

Type	2017	2020
Heating	5,450	10,090
Cooling	5,690	10,540
Hot water	890	1,640

### **Gas load**

The residential heat quota was 2300 MJ/person • year, with a gasification rate of 100%. According to the scenario, the industrial gas consumption data was 1 m<sup>3</sup>/100m<sup>2</sup>•day. The storage gas consumption indicator was 0.2 m<sup>3</sup>/100m<sup>2</sup>•day, and gas consumption of the thermoelectric cooling triple for direct gas turbine was 1 m<sup>3</sup>/100m<sup>2</sup>•day. Based on the above analysis, gas load of this city in short- and long-term can be calculated (see table 3).

Table 3. Gas load

Load	2017	2020
Annual gas consumption (10 <sup>3</sup> m <sup>3</sup> )	20,030	42,950
Annual average (m <sup>3</sup> /d)	54,873	118,154
Calculate monthly average day (m <sup>3</sup> /d)	65,566	151,066
Peak hours (m <sup>3</sup> /h)	9,316	18,587

### **Electricity load**

The electricity load in the eco-city is divided into five categories: residential, public facilities, industrial, commercial, and others. Load forecasting is carried out according to the density data method, and the effect of energy saving measures is determined. The prediction results in electricity load of 108.14 million kwh, with a load density of 20.1 MW/km<sup>2</sup>.

### **Energy structure and evaluation**

In consideration of the energy situation and natural resources in the eco-city, Energy use model is based on conventional energy, distributed energy, industrial waste heat, new energy and renewable energy supplement, all kinds of energy complement each other. This will ensure that the urban energy supply is safe and reliable, reducing the green eco-city carbon emissions.

### **Distributed energy systems**

The core business district area is about 1,770,000m<sup>2</sup>. The energy supply station uses natural gas as fuel for the region to provide CCHP, because of energetic and electrical safety requirements, and can reduce energy consumption by 60%.

### **Industrial waste heat utilization system**

Power plants can circulate low temperature water resource waste to improve their comprehensive energy efficiency, and reuse waste heat. Urban power plants have a heating capacity of about 20 million m<sup>2</sup>, and accounting for pipeline transport distance, heat, and other factors, an area of about 8.6 million m<sup>2</sup> in the planned construction area can receive energy from Jinan City power plant using waste heat.

### **New Energy and Renewable Energy Systems**

#### *Solar photovoltaic, light and heat resources assessment*

The eco-city is located in an area with a warm, temperate, semi-humid monsoon climate. The average annual solar radiation intensity is 330 W/m<sup>2</sup>, average daily sunshine duration of

6.9 h, annual sunshine duration of 2,516.9 h, total annual radiation of 5120.50 MJ/m<sup>2</sup>, and average solar radiation intensity of 330 W/m<sup>2</sup>. Areas where the daily sunshine duration is greater than 6 h, and average monthly temperature is greater than 10 °C for 239 days, are rich in solar energy resources, and have the potential to develop solar thermal and solar power industries.

Solar energy supply potential is calculated as Solar energy supply potential (kWh) = land area × planned building density × annual total solar radiation [MJ / (m<sup>2</sup>·a)] × usable roof area rate (%) × solar cell area and usable roof area (%) × solar power supply system conversion efficiency (%) × building photovoltaic curtain wall application additional coefficient(see table 4).

Table 4. Estimation Coefficient of Solar Photovoltaic Supply Capacity

Building type	Roof utilization rate	Battery pack / roof area	Photoelectric system conversion efficiency	Additional coefficient of photovoltaic curtain wall
Business	40%	50%	15%	1.2
Office	40%	50%	15%	1.5
Market	40%	50%	15%	1.0
Community service	20%	50%	15%	1.0
Education	60%	50%	15%	1.0

Public buildings with solar panels can provide 0.19 billion kWh of electricity, only considering the provision of living electricity demand and ignoring the comprehensive energy efficiency of solar photovoltaic systems, system investment recovery period, and other economic factors, reducing coal use by 0.69 million tons.

Solar heat can be used in residential lands, primary and secondary schools, and other plots, which are large-scale uses of solar resources. Other uses of a centralized solar water heating system in residential and commercial land development can demonstrate the suitability of a solar thermal system. If the solar panels in the eco-city area region provide heat of about  $22 \times 10^8$  MJ, this provides 60% of residential buildings' energy requirements

#### *Evaluation of shallow geothermal energy resources in soil source*

The distribution of geothermal soil heat in the ecological city area is within 100-400 meters of the surface, and the temperature of the soil and groundwater equal to the local average temperature, and is not affected by the environment or climate. Throughout the year the heat fluctuates but maintains a balance.

Utilizing shallow soil geothermal energy is suitable for areas of smaller building density. According to the plans for the eco-city, the construction area for the low-density residential area, basic education, community services, and the other buildings with smaller building density is in the northern part of the zone, with an area of 800,000 m<sup>2</sup>.

#### *Evaluation of shallow geothermal energy resources for surface water sources*

In the planning area, annual runoff from the river is large, and water flow is good; however, due to large temperature differences between the river and the water source, the water source can not be used for the water heat pump. The city can not use a river water heating pump system for water resource protection, and other reasons.

### *Wind energy resource assessment*

Jinan has an effective wind energy density of  $150\text{-}200 \text{ W/m}^2$ , which can be combined with the river landscape and solar-wind complementary street lamps.

### **Energy planning conclusions**

Through the analysis of the attributes of the new city and the potential of local renewable energy resources, this paper analyzes new and renewable energy generation and utilization strategies, and provides support for optimizing the energy structure of the new city. New energy and renewable energy in this zone will generate about  $100.14 \times 10^7 \text{ kWh}$  by 2020, with carbon dioxide emissions of 356,900 tons, a renewable energy utilization ratio of 15.19%(see table 5), waste heat utilization of 3.03%, and clean energy utilization rate of 100%.

Table 5. New energy and renewable energy replacement rate

Energy type	Quality ( $10^3 \text{ kWh}$ )	Annual Occupancy ratio(%)
Solar heating	782,028	11.98
PV	197,100	3.02
Shallow soil geothermal	6,700	0.15
Wind energy	1,670	0.04
Total	987,498	15.19

### **Conclusion**

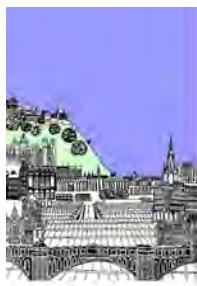
To develop a scientific and rational renewable energy utilization plan for an eco-city, energy demand should be forecast, and new and renewable energy resources assessed and combined with new and renewable energy conversion system performance characteristics. It should be conducted that analysis of construction sites for renewable energy supplies and energy demand; and new and renewable energy engineering practices should be established based on new and renewable energy capacity, preference, reliability, stability, technical difficulty, economic and environmental conditions, and other aspects of the evaluation. An applicability priority gradient, and the establishment of engineering feasibility criteria, will be of use for a renewable energy target assigned to each area of land and will help achieve the goal of ecological planning.

### **Acknowledgment**

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### **References**

- Phil Jones (2016). Ecocities—A Bottom-Up Project Driven Approach, *Urban Environment Design*,101(06) ,193-197
- Phil Jones, Xiaojun Li, Shanshan Hou (2016). Urban Scale Energy Modelling in the Built Environment, *Urban Environment Design*,101(06) ,254-265
- Huang Jianxiang, Wang Yali, Peng Rong (2016). Urban Microclimate & Pedestrian Comfort in Dense Cities, *Urban Environment Design*,101(06) ,266-27
- Shandong Province Residential Building Energy Efficiency Design Standards (DBJ 14-037-2012)
- Urban Heating Pipe Network Design Specifications (CJJ 34-2010)



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## Prediction of electricity demand with artificial neural networks – an example of the Ontario province in Canada and the Italian market

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**Abstract:** The study describes possibilities to predict the electricity demand with artificial neural networks. Empirical research includes energy market of the Ontario province in Canada and the energy market in Italy. Numerous network models of MLP, GRNN and RBF architecture were subjected to tests. Delayed values of energy demand, variables of technical analysis and meteorological data, as well as calculated on their base index have been used as the independent variables. Cyclical character of the energy market was taken into account in selection of the set of input variables. Verification of the quality of MLPs network prediction was conducted in the test, which neurons contained activation function in a form of logistic function, hyperbolical tangent and exponential function.

**Keywords:** electricity demand, neural networks, energy markets, artificial intelligence, prediction

### Introduction

Artificial neural networks (ANN) belong to tools from the area of artificial intelligence. Their origin dates back to the year 1943, in which the first mathematical model of neuron was presented (McCulloch, Pitts, 1943). The scheme of artificial nerve cell presents Figure 1. Inputs – indicated  $x_1$  to  $x_n$  constitute the equivalent of biological dendrites, i.e. structures responsible for entering signals to biological nerve cell. In the artificial model with each of recalled inputs ( $x_i$ ) a certain real number indicated in Figure as  $w_i$  is connected. Signals entered into the cell are multiplied by the real number assigned for the input, in this way products will be calculated and then summed up. In the next stage, the established value is transformed with so-called activation function. Described weights are the basis of ANN function. In the study they are subjected to modification and thanks to that process the network acquires knowledge.

The recalled activation function has the task to simulate signal transformations occurring in the nucleus of biological cell, as well as partly within the synaptic connection. Action potential in the biological cell in communication process has de facto character of continuous function and usually changes in a range from about -40 to +70 mV. Also far better are continuous functions in ANN during market analyses. Amongst the most commonly applied are logistic function, hyperbolical tangent, sine and Gauss. After described transformation the signal is derived from the cell using the output Y (equivalent of biological axon) and goes to the cells of other layers or constitutes the output signal of model (there are possible derogations from described principles, for example in some

recurrent neural networks the signal can be transmitted to the same nerve cell or other neuron of the same layer).

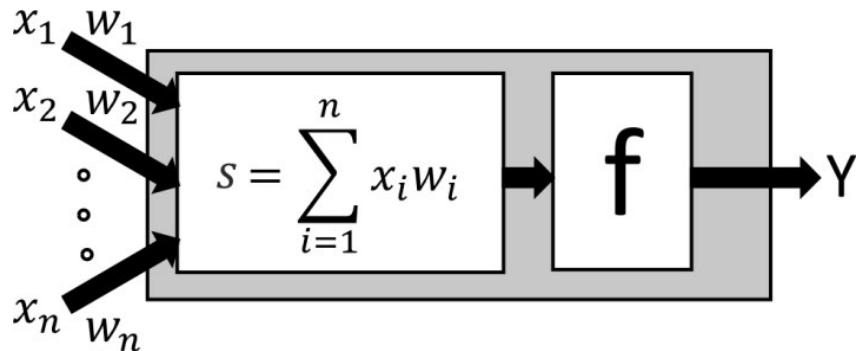


Figure 1. Artificial neuron scheme (Jasinski et al., 2016)

Depending on connections between neurons and flow direction of signals, there are distinguished different types of ANN. Research was conducted using three types of networks – multi-layered perceptron (MLP), radial basis function networks (RBF) and generalized regression neural network (GRNN). They all have one-way architecture, this means that signals are transmitted from input to output, and in the network there are no feedbacks (which are characterized by recurrent neural networks).

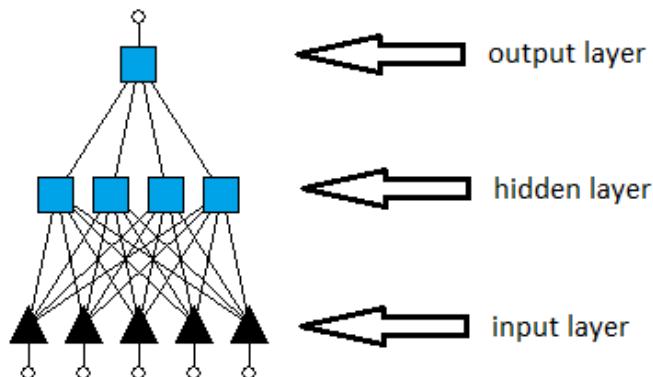


Figure 2. MLP scheme

Figure 2 shows an example of MLP scheme created based on single hidden layer. It should be noted that only cells in hidden layers (there can be many of them – most often applies one or two such layers) and always single output layers are subjected to the process of study (modification of weights). Neurons of input layer are not subject to the process of study, and their role is to collect data from the outside of model and their distribution inside the network. The number of cells in this layer depends from the number of independent variables of the model. By analogy, the number of cells in output layer corresponds to the number of dependent variables. An attempt to predict the electricity demand was carried out in this study. This indicates a need to equip output layer in only one neuron. The number of cells in a hidden layer must be selected experimentally (in the subject literature it is possible to find suggestions as for their selection, however they are often contrary and do not lead to optimization of the model. In each case individually and experimentally it is necessary to select their optimum number and parameters).

## Energy markets

Energy markets in two countries have been analyzed: Canada (Ontario province) and Italy (IPEX). This selection was not random; due to different climate it is necessary to expect different structures of energy demand in both countries. An aim of the study was to present the possibility of using ANN to predict the energy demand at different nature of demand. In spite of certain differences, almost all energy markets have a lot of common features. One of the most important is cyclical nature of demand. In practice, peculiarly visible are three cycles of periods: annual, weekly, and daily. Figures 3 and 4 show the cyclicity of demand for energy market in Ontario province. On Figure 3 (annual cycle) it is possible to observe two peaks. The first appears in summer (when in the highest degree air-conditioning systems are used), and second in winter (during a fall in temperature). As it is easy to notice the demand for energy is reduced in the time. At the present time it is a trend, which appears in many countries with relatively high labour costs or inclined to highly qualified work. It directly involves occurring deindustrialization process that results in transfer of production (as a source of high energy demand) to countries with lower labour costs and productions.

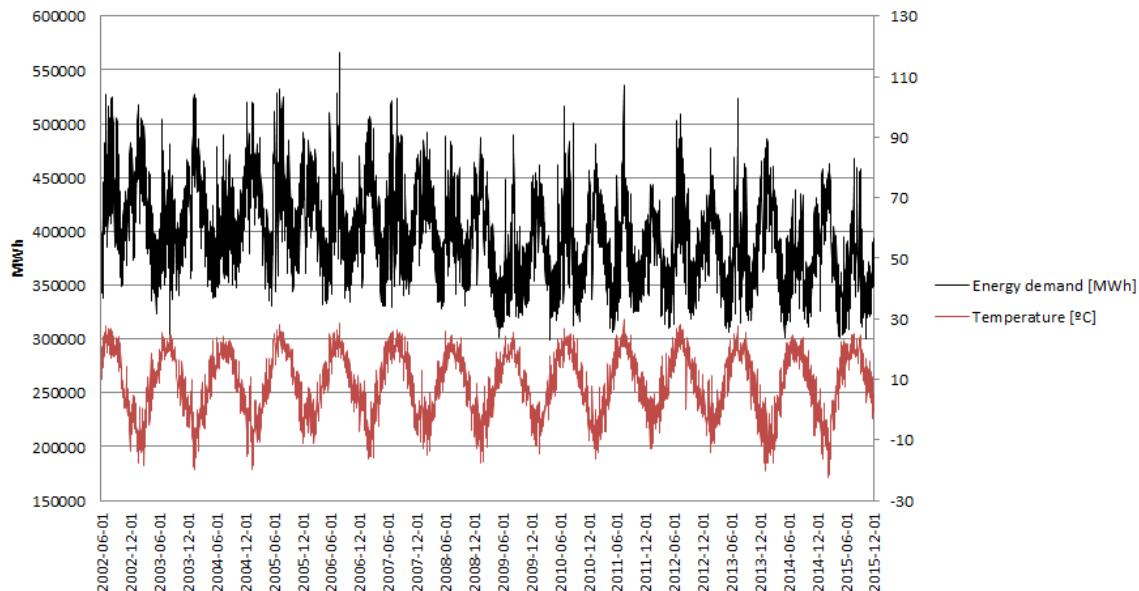


Figure 3. Annual cycles of the electricity demand (Ontario province in Canada)

In spite of reducing in the time average energy demand, the maximum consumption usually does not indicate this type of trend. Increasing living standard of modern societies directly related to the use of many electric devices, above all air-conditioning systems in summer, as well as heating periods in winter (HVAC). This causes that in many countries the energy system must meet the growing peak of energy demand. This situation constitutes a particular treat for continuity of supplies in those countries, which do not have energy production and distribution systems. As the example is Poland, in which predominant coal power stations are not equipped with dry-cooling systems. Traditional and currently considered obsolete water-based cooling systems are a real problem in the summer months. High temperature causes an increased demand for energy due to more popular air-conditioning systems, and at the same time reducing level of water prevents efficient cooling and forces generators to reduce the production of electricity in the peak demand.

This may involve the need to limit energy supply or even occurrence of interruptions in their supply. The first of these situations took place on 10 August 2015, when it was necessary to announce the twentieth power supply level resulting in restrictions of electricity consumption by companies.

Similar threats of preserving the continuity of supplies may concern countries using highly renewable sources. On 20 March 2015, solar eclipse caused a dramatic drop in generating capacity of generators in Germany, in which solar power stations have a high share of total electricity production.

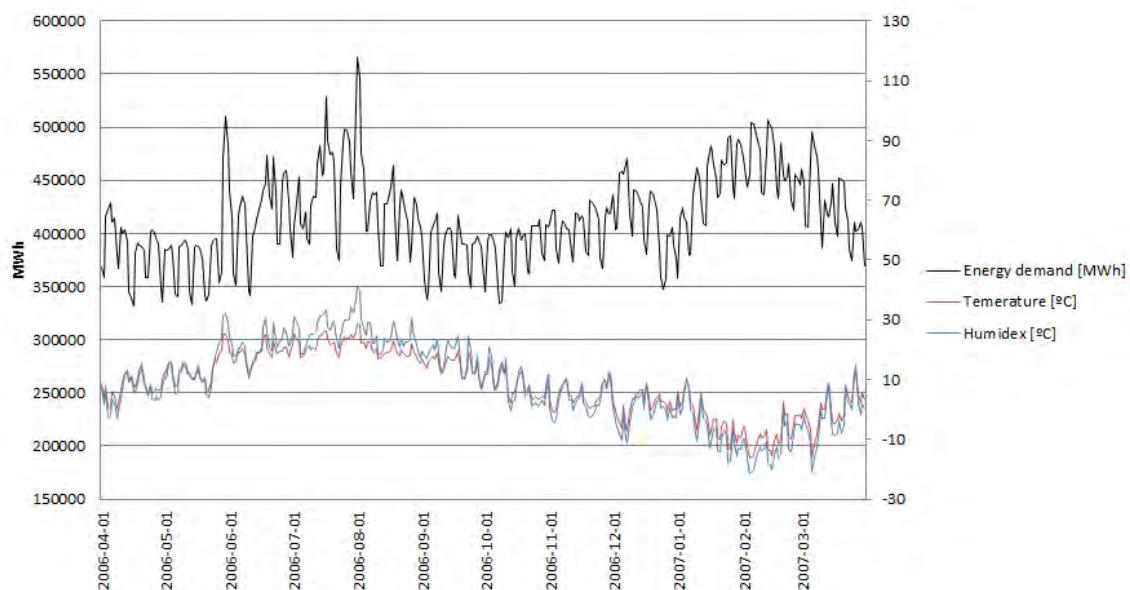


Figure 4. Weekly cycles of the electricity demand (Ontario province in Canada)

This shows how important is the possibility to predict energy demand both in terms of total and peak. The precision of these predictions constitutes the key element of providing the continuity of supply, and affects the energy price by not-incurring costs associated with maintaining large reserves of its production.

Weather conditions are one of basic elements determining the height of demand, in particular air temperature and wind speed. Amongst other atmospheric factors commonly lists the air humidity, which taken into account in the model is also possible by using such index as for example humidex. Figure 3 presents the electricity demand with a chart of air temperature. As can be seen the peak energy demand coincides with extreme temperatures. The peak demand appears, as it was possible to expect, both in the summer and winter. Provided direction of changes of the electricity demand to a large extent is consistent (in cooling season) or opposite (in heating season) to the direction of temperature changes, then dynamics of these changes are often different. A much higher level of compliance it is possible to observe between dynamics of changes of the electricity demand and dynamics of changes in humidex index (Figure 4). A new type of input variable based on humidex index was used in empirical studies due to changing nature of dependencies between them along with the change of cooling season on heating (and inversely). The original index value was used for the temperature higher than 17°C (this value generally is regarded as a transition temperature from heating to cooling), however for lower temperature the index value was specific as 34-humidex. Such a rate is characterized in much large degree by one-way relation towards the electricity demand (Figure 5).

Analogous – cyclical – behavior in demand it is possible to observe on the Italian energy market. Figure 6 shows its changes over time based on data obtained from IPEX. Also here within the last few years a fall in the trade of electricity is observable, as well as peak volumes in summer months, usually above winter maxima.

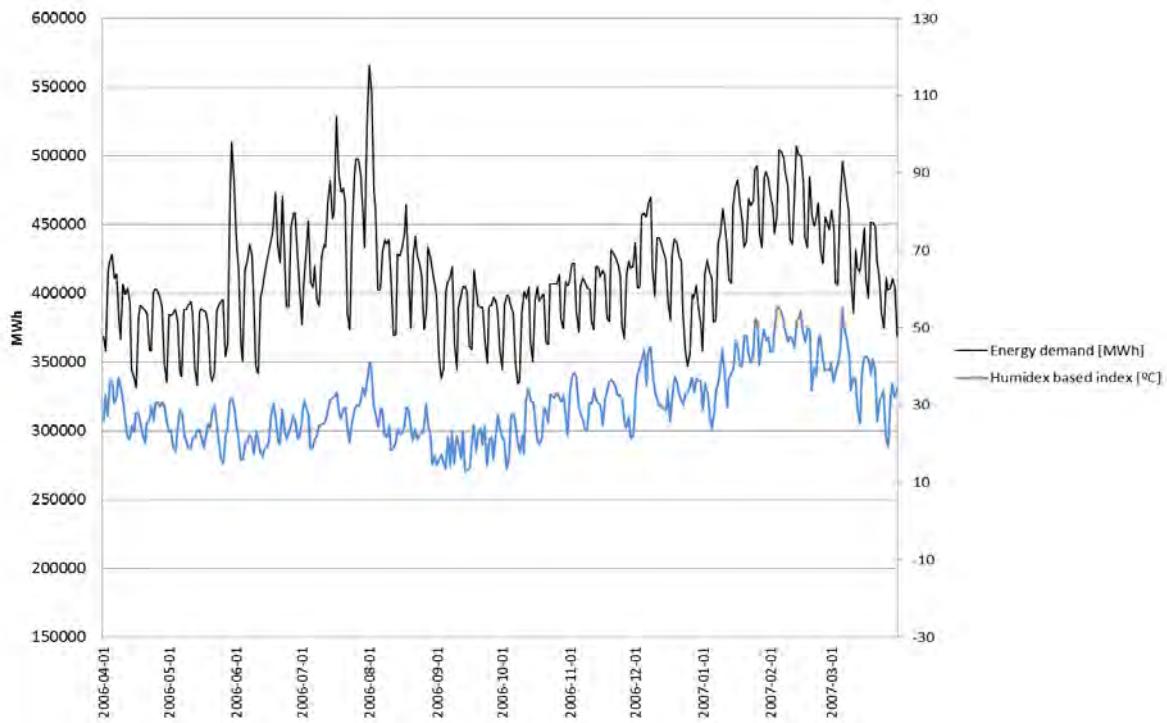


Figure 5. Modified humidex index and electricity demand (Ontario province in Canada)

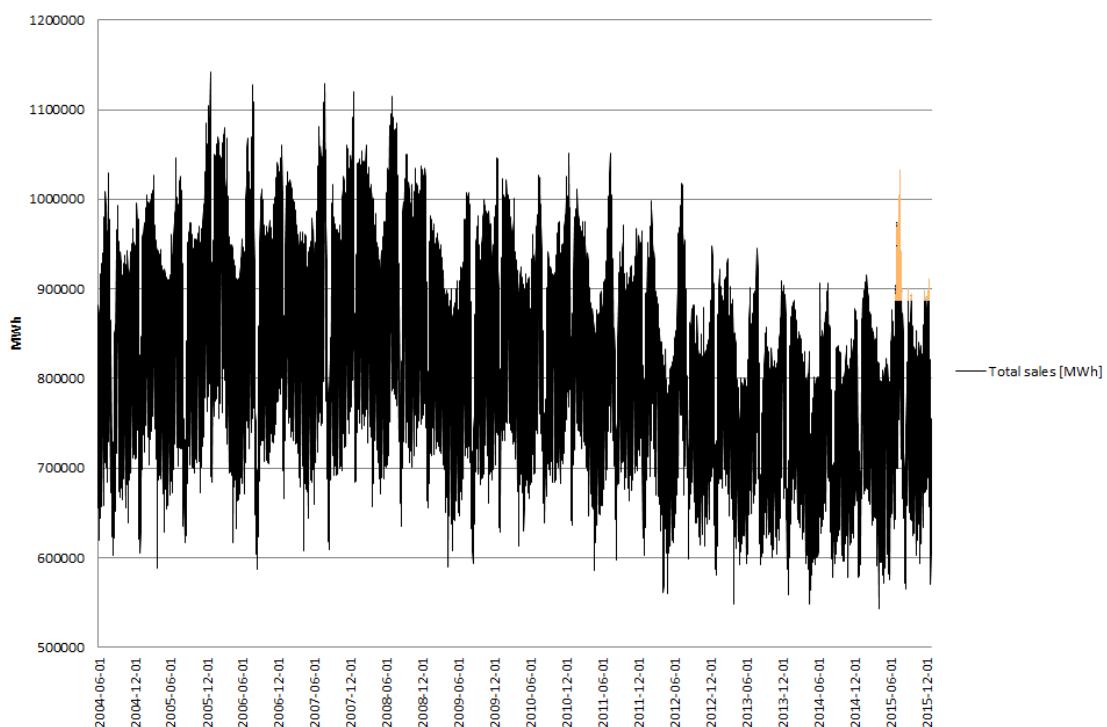


Figure 6. Sales volume of the electricity (IPEX)

## Day-ahead demand forecasts – empirical studies

Figure 7 presents MLP scheme with regard to daily forecast of energy demand in the Ontario province in Canada. ANN was built from 8 neurons in input layer, 13 in hidden and single cell in output layer. Cells of hidden layer were built using activation function in a form of hyperbolical tangent.

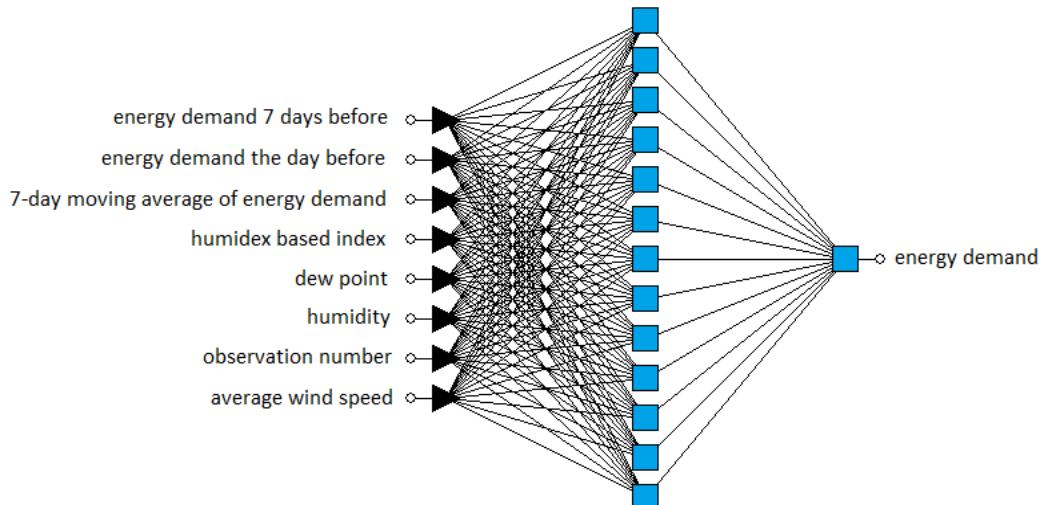


Figure 7. MLP scheme predicting the electricity demand (Ontario province in Canada)

Figure 8 presents percentage error histogram (PE) of predictions for data from the test set. The largest number of predictions was an error from the range of 0% to 2% caused with revaluation future demand. The second group of predictions – in quantitative terms – constituted those in which the demand for energy has been overestimated between 0% and 2%. This result should be considered highly satisfactory.

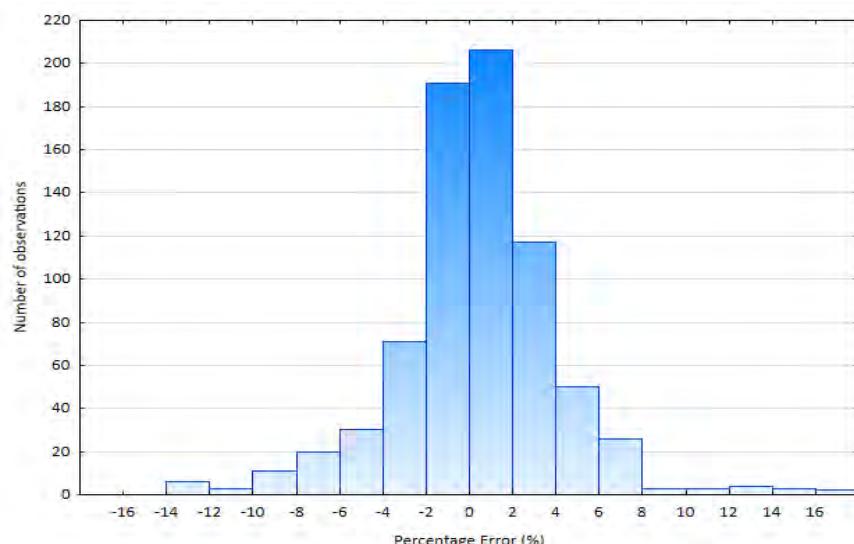


Figure 8. Percentage error histogram of the prediction for data from the test set (8 input variables, Ontario province)

It is widely believed that efforts should be made to possible simple ANN structure, because each of neurons, in addition to affecting the growth of potential networks,

generates signals with a certain error. The last ones – which results from the principles of neuron and ANN structure – are then added and affect the total error of prediction. Far-reaching simplification of the model was conducted in the next stage of research, among others by elimination from independent variables of selected meteorological data. The best resulting model contained only five input variables in a form of: (i) energy demand the day before, (ii) energy demand 7 days before, (iii) 7-day moving average of energy demand, (iv) humidex based index, (v) dew point. The number of neurons in next layers was: 5, 10 and 1. As in previous studies, also here hyperbolical tangent function was used as the role of activation function of neurons in hidden layer. Percentage error histogram (PE) of the simplified prediction model was presented in Figure 9. As can be seen, removing from the model a part of independent variables resulted in deterioration of the prediction quality, in particular by increasing the number of errors caused by underestimation of the energy demand in a range between 2% and 4%.

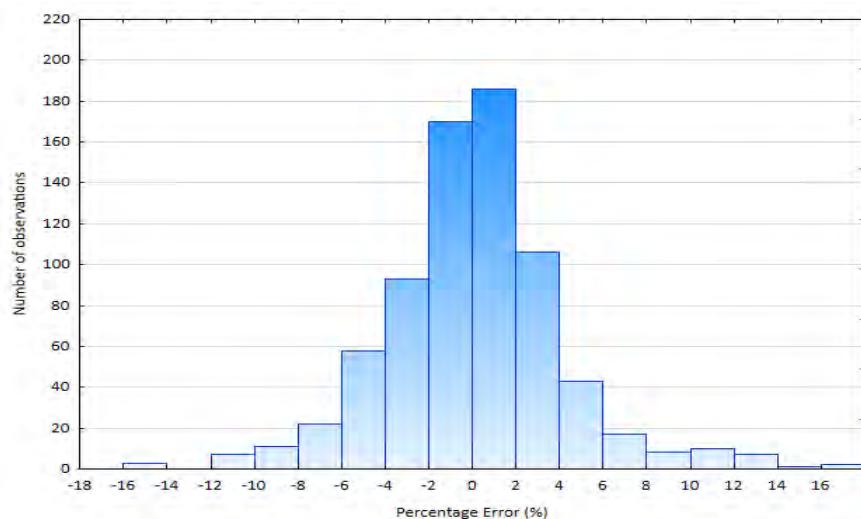


Figure 9. Percentage error histogram of the prediction for data from the test set (5 input variables, Ontario province)

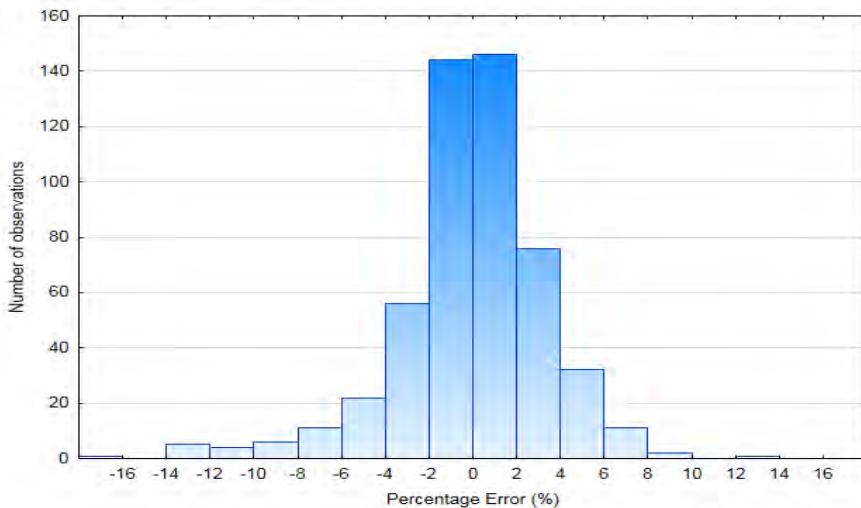


Figure 10. Percentage error histogram of the prediction for data from the test set (8 input variables, IPLEX)

Similar results were obtained in case of daily forecast of the sales volumes of electricity on the IPLEX. Studies were conducted using the same input variables as previously. Percentage error histogram (PE) of obtained prediction was presented in Figure 10.

## **Conclusions**

Conducted studies confirm the possibility to predict the electricity demand with high precision. Obtained results show that the number of prediction errors related to reevaluated demand for energy is greater than the number of errors related to its underestimation. However, these differences are not significant. Studies have shown that reducing the amount of input variables of meteorological type adversely affects the quality model. The process of tests confirmed great potential of MLP architecture, which turned out to be in the analyzed issue better than networks of GRNN and RBF type. The test confirmed the validity of applying modified humidex index as the independent variable. It turned out to be one of the best input variables of all models, without which obtained results were significantly worse.

Particular attention should be paid to the fact of confirming the possibility to conduct precise prediction of the electricity demand on different markets, with different weather conditions, and thus different structure of the demand for energy.

This study does not exhaust the subject of predicting the electricity demand. Further improvement in results it is necessary to seek in the area of optimization the set of input variables. In particular, it is necessary to consider applying other tools of technical analysis.

## **References**

- Italian Power Exchange (2017). *Historical data*. Available at: <https://www.mercatoelettrico.org/En/Download/DatiStorici.aspx> (Accessed: 3 January 2017)
- Jasinski, T., Marszal, A., Bochenek, A. (2016). *Selected applications of artificial neural networks in the currency market, futures market and spatial economics* (in Polish). Lodz: Lodz University of Technology
- McCulloch, S., Pitts, W. (1943). A Logical Calculus of the Ideas Immanent in Nervous Activity. *Bulletin of Mathematical Biophysics*, 5, pp. 115-133
- The Independent Electricity System Operator (2016), *Data Directory*. Available at: <http://www.ieso.ca/power-data/data-directory> (Accessed: 5 October 2016)



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Land Suitability for Wind Farms in Suez Governorate, Egypt

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**Abstract:** By the development of the industrial technology, the greenhouse gases (GHG) emissions increased, which contributed to the phenomena of climate change. This research is concerned with using the renewable energy source of wind farms as a tool to reaching zero carbon dioxide gases emissions. This is also part of the new Egyptian vision that aims to increase wind power capacity to 20% by 2020. In line with this vision, the aim of the research is to find the suitable lands in Egypt to accommodate wind farms in Egypt. With the variety of variables affecting wind farms' locations as well as the density of current land uses in Egypt; it is important to find the suitable tool that could conduct these types of analysis. The research used the land suitability analysis conducted by the geographical information systems (GIS), in which multi criteria could be used to identify the appropriate locations. Different variables affecting the presence of wind farms could be added and overlaid in GIS including wind speed maps, wind directions map, and topography maps. The findings of this research help identifying the suitable locations in Suez Governorate in Egypt that could accommodate wind farms.

**Keywords:** Global warming, Climate change, Wind farm, Geographical Information System (GIS), Land suitability analysis.

### Introduction

Global warming and climate change are important phenomena that appeared in the last century. Their appearance depended on the significant increase of temperature that resulted from the presence and development of the industrial revolution (Organization, United Nations, 1992). The awareness of the earth's population increased and led to finding solutions that could help facing this problem. Most of environmental sector governments started to set certain regulations to reduce the phenomena of global warming and climate change by using renewable energy sources.

For Egypt, the highest percentage of greenhouse gas emissions is coming from indirect sources: i.e. burning fuel in transportation and producing goods for consumers. According to the climate investments fund, Egypt is the 11 speediest country producing greenhouse gas (GHG) emitting nations on the world. The climate investments funds warn and expect to exceed the percentage of the greenhouse gas (GHG) emissions to 300% by 2017. The increase in population (range up to 2.6% per year) in Egypt will also lead to increased use of energy, which by its turn will effect on the Egyptian economy (Funds, 2005). The energy industry and transportation sectors emit a lot of carbon intensive. The percentage of carbon footprint emitted from the transportation sector and power generation are calculated to be 42% and 21% respectively of Egypt's total GHG emissions (Funds, 2005). The government is now heading toward building stations for generating a renewable energy: i.e. Wind Farm, and

Solar panels aiming to reduce the greenhouse gas emissions that contribute to climate change. Wind farms are one of the sustainable projects encouraged nowadays. They consist of number of turbines located in certain place (sea or land) to generate electricity. This type of energy has been enlarged by governments especially after the oil crisis in 70's (Harborne et al, 2009).

This study sheds light to the concept of global warming and climate change in Egypt. It focuses on the wind farms as an important renewable source of energy. The main aim of this research is to locate through the Geographical information systems (GIS) the best suitable lands in Suez Governorate, Egypt that could be able to accommodate wind farms.

## Literature Review

During the past few decades, the Geographic Information System (GIS) have been used to find the suitable location for wind farms' installation (Rodman, L.C et Meentemeyer, R.K, 2006). GIS collects large geospatial information as criteria and integrate them into decision-making to install wind farms. Baban and Parry (2001) set 14 criteria (including slope, land use, and historic site) based on data collection from literature review and questionnaires to identify the suitable location of wind farms in the United Kingdom by using weighted overlay analysis in GIS. In the same way, Janke (2010) applied multi-criteria GIS modelling to find the best location for wind farms in the State of Colorado, U.S. The criteria involved the wind potential; distance to cities and roads; and population density, all collected from the geospatial databases. The data were converted into raster data and overlaid to suitability map located in north-eastern Colorado. According to the previously mentioned factors, Van Hoesen and Letendre (2011) added new criteria such as new ecological and economic aspects to reduce the total cost and avoid bird migration. The visual impacts of wind turbines in State of Vermont were taking into consideration as another critical factor of view added by Van Hoesen and Letendre (2010). Rodman and Meentemeyer (2006) used certain rules in GIS modelling approach to determine the suitability map of wind farms in Northern California, U.S. The factors were classified into three categories, being physical, environmental and socio-economic. In south-western Taiwan, they used similar approach to locate wind turbines (Yue and Wang, 2006). In Egypt, Effat, H., (2014) had two types of factors. First factors contained wind speed, elevation of zones to get wind power density and the second factors included economic factors such as distance from roads, power lines, and urban areas.

Table 1. Study areas, modelling approaches and factors adopted by studies on land suitability for wind energy development (modified from Szurek et al., 2014).

City	Source	Approach	Factors
Western Turkey	Aydin et al., 2010	Multi-criteria decision-making with fuzzy set theory	Distance to: natural reserves, large cities, from towns, distance from airports, noise, from lakes and wetlands, wind power.
United Kingdom	Baban and Parry, 2001	Multi-criteria analysis & questionnaire	Slope, distance to water bodies, historical sites, urban areas, roads and railways, land use and the presence of important ecological areas
Colorado, U.S.	Janke, 2010	Multi-criteria analysis	Wind potential, distance to transmission lines, distance to cities, population density, distance to roads, land cover, federal land
Northern California, U.S.	Rodman and Meentemeyer, 2006	Rule-based spatial analysis	Physical criteria: wind speed, forest density, valley slope and distance to ridge; Environmental criteria: vegetation, endangered plant species and wetlands; Human impact criteria: urban areas and recreation areas

New York, U.S.	Van Haaren et Fthenakis, 2011	Multi-stage multi-criteria analysis	Economic evaluation: distance to transmission grid, distance to roads, land clearing costs, wind resources; Bird impact evaluation; Excluded locations: urban areas, federal lands, reservations, roads, lakes, steep slopes, karst areas; Planning criteria: noise Van
Prusice, Poland	Szurek, Blachowski and Nowacka, 2014	Gis-based multicriteria analysis	Location of nature protection areas and their buffer zones, built-up areas and their buffer zones, location and distance from power lines, location and distance from rivers and surface waters, location and buffer zones from forests, - location, technical standards and distance from roads, location, technical standards and distance from railways, slope, aspect, location and distance from telecommunication lines
Red Sea Governorate, Egypt	Effat, 2014	The Analytical Hierarchy Process	First factors are wind speed, elevation zones used to derive the wind power density. Second factor is economic factors involved distances from urban areas, roads and power-lines. Third, land constraints were derived from the evaluation.
Poultney Valley, Vermont, U.S.	Van Hoesen and Letendre, 2010	GIS-based overlay analysis	Wind potential, view shed for visual impact including heights of canopy, slopes and elevation

In this paper Land Suitability Analysis, based on Geographic information system (GIS), will be applied in Egypt to identify the suitable place for wind farm. By using Geographic information system, the identifying suitable land based on current land use maps, water network system maps, climate maps within maximum temperature and minimum temperature, rain fall time, wind speed maps, wind direction maps, humidity and bird migration. Every map of this information has different raster layers with another scale. The urban planner could not combine with two different units of raster layer such as: raster of ground water in (m<sup>3</sup>/year) within raster of climate (m<sup>3</sup>/year). The selection of the suitable land for Wind Farm is based on: Wind Resources, Roughness of the terrain and obstacles, Road Access, Orography of the region, Accessibility to transmission and/or distribution networks, Soil Conditions, and Environmental Impacts Obviously (Baban& Parry, 2001).

## Methods

### ***Description of the Suez Governorate, Egypt***

Suez governorate coastline is located on the northern part of the Gulf of Suez between latitude 29° 58' 25.36"N and Longitude 32° 31' 34.57" E. The Suez Governorate is bordered from the north by Governorate of Ismailia, north Sinai Governorate, from the south by Red Sea Governorate, from East bounded by South Sinai governorate, and from West bounded by Cairo Governorate and Giza Governorate. The area of the governorate is 10,056.43 miles. The weather condition in Suez is known by a desert climate. In Suez, there is almost no rainfall during the year. The Suez governorate is identified by a dominantly hot and windy climate. In Suez city, the average temperature is 22.7°C. The annual relative humidity is 53.5%. The annual evaporation is 9.6 mm per day. The wind speed in some zones reach 7.9 m/sec, and in other zones may reach 11.7 m/sec which is high potentials for Wind Energy. The average of rainfall is 20 mm. May is the driest month and has 0 mm of precipitation. Rainfall starts in

November. The warmest month is August. The minimum temperature is 14.8°C in January, and average temperature is 29.8°C.



Figure 1. Suez Governorate of Egypt Map

### ***Selection of Model Factors***

There are 5 criteria selected for doing suitability analysis to find the suitable location for wind farms. The criteria are Wind Energy potentials, Powerline, Roads, Slopes, Shoreline, and Exclusionary areas (i.e. Cities and Towns). The selection of the criteria is based on the comprehensive literature Review. These crucial criteria are to identify suitable location for Wind farms installation in Suez Governorate. The layers were projected co-ordinate system into UTM 1984 Zone 36N, and then turn these layers into raster data structure. Table 2 shows the criteria, data source, Reasons for Selection, Original Data Structure, and Original Data Structure.

Table 2. Criteria and source of Data used in model and Criteria and Excluded zones (Constraints) threshold.

Criteria	Data Sources	Reasons for Selection	Source	Buffer zone (m) around excluded zones
Wind Speed	Effat, H., (NARSS)	Important for wind energy production	Vector (Polygon)	
Slope	Effat, H., (NARSS)	Slope affects the ease of construction & maintenance	Raster	More than 9 degrees
Power Lines	Effat, H. (NARSS)	Ease in connection of electricity	Vector (Line)	250 m around Power lines
Cities & Urban settlements	Effat, H. (NARSS)	To reduce visual and noise impacts	Vector (Point)	2000 m around Cities
Land Use/ Land Cover	Effat, H. (NARSS)	Show environmental impacts	Raster	
Shoreline	Effat, H. (NARSS)		Vector	4000 m around Shoreline
Roads	Effat, H. (NARSS)	Ease of access for maintenance.	Vector (Line)	500 m around Roads

### ***Criteria and Thresholds***

These criteria can be used by environmentalist to identify the best location. For example, distance of wind farms installation and bird migration to reduce bird collisions, and to avoid visual impacts and noise for population zones. The most important criteria for installing wind turbine are the wind energy potentials and environmental fitness. While selecting the site, the criteria of wind energy potential and environmental acceptability must be taken into consideration. Moreover, any location that don't have enough or adequate wind energy will be unsuitable for selecting wind turbines. Figure (2) represents a flow chart for the criteria and methodology being used.

## **Power-Lines Proximity and Setback Buffer**

According to Nextra Energy Canada (2011) and, Bartnicki and Williamson (2012), the production cost is minimized by choosing a suitable location to be near to hydro lines and roads. Furthermore, the transmission line distance has to be short for transporting the wind turbine energy and minimizing cost. To maintain a suitable site, the land is linked to electrical grid. According to Moiloa (2009) and the DEADP (2006) a minimum distance were suggested by them, that about 250 meter must be apart from any high voltage.

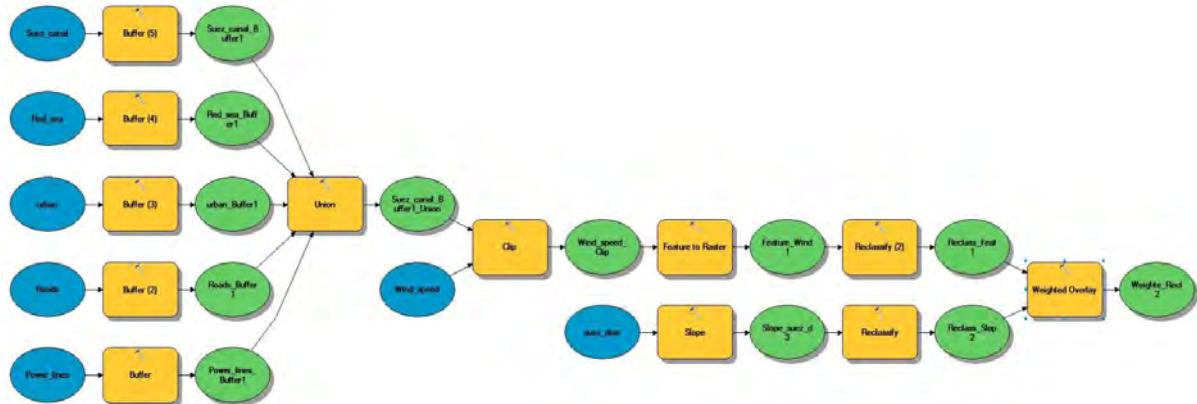


Figure 2. A conceptual chart for the applied methodology

**Urban Areas and Cultural Sites Proximity and Setback:** According to the CNDV Africa report (2006), the legacy sites as civilized and historical value with provincial or national name are clarified. These types of sites are categorized as educational amenities that must be protected carefully. Williamson and Bartnicki (2012) granted a 550-m setback for historic areas, recreational and urban. For the present study, historic sites used a setback of 1000 m however for the cities growth expansion a setback of 2000 m where used.

**Slopes:** Bartnickiet Williamson (2012) and Luo et al. (2007) reported that the probability of the turbine failure is increasing when the slope is higher than 9 degrees as it is difficult for the wind to hit the rotor of the turbine perpendicularly at the summit of steep. Therefore, if the slope of exceeded 5 degrees this will harvest a high turbulent wind pattern causing instability in the wind turbine. In addition, the project cost highly increases if the buildings are on high slopes. Baban and Parry (2001) suggested that the terrain or zone must be flat or rounded to be able to tolerate high wind speeds. The classification of the slope was most suitable for 5 degrees; marginally suitable less than 10 degrees and slopes more than 10 degrees are totally unsuitable.

**Ecological and Social Factors (Exclusion Zones/Constraints):** Social and ecological evaluation criteria could be factors or constraints. A constraint is restrictedly inappropriate zone for installing wind turbines. According to Bennui et al. (2007), for protecting effect, it is excluded on communities, environment, eco-conversation and visualization. Moreover, according to Effat and Hegazy (2013) and Effat (2014) constraint standard has assigned as a threshold.

**Shoreline Setback:** The Wind farms must be far away from any residential areas. Moiloa (2009) and DEAP (2006) suggested the distance for the wind farm is to be far away from the coast for about 4 km. Around the shoreline, identical buffer zone was applied taking in consideration the paths for bird flight and future marine activities for tourism.

**Land-Use—Land-Cover:** Land such as airports must be kept away from any wind farms as the operations can affect navigation. A setback for about 25 km between the wind farm and the airport is identified by CNdV Africa (2006).

**Standardization of the Criteria:** Saaty's (1980) identified that the suitable standardized scale is to be from 1-9 converting the original values to a suitability value. Bartnicki and Williamson (2012) suggested that the high score will be for higher suitability.

## Results and Discussion

The study accomplished by using Geographic Information System (GIS) for mapping the suitable location in Suez Governorate for siting wind farms. In the analysis, the modelling framework based on multi-criteria of GIS is identifying the suitable sites for wind farms installation with cost effective techniques. Engineering, socio-economic and environmental criteria were taken into considerations. Based on results and output of the maps in Figure 3, these criteria should identify the best location for wind farms according to each factor. The design of weighting and scoring was based on literature review and related studies. Other criteria such as utilities, governmental agencies, and demand investor were added for the modelling framework to be more accurate and to develop the layers of geospatial for those criteria.

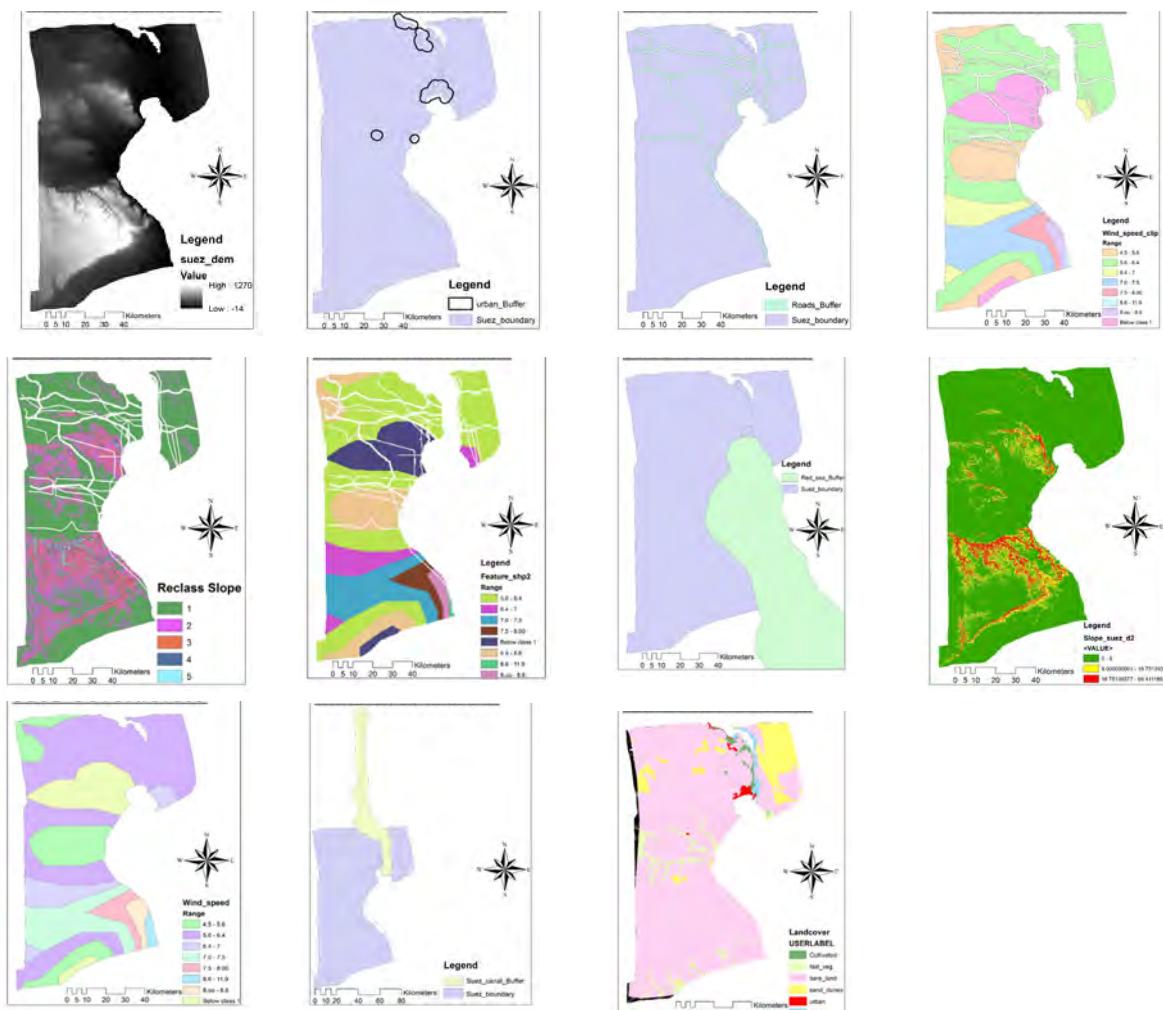


Figure 3. Spatial patterns of suitability scores for each criterion (exclusionary area excluded).

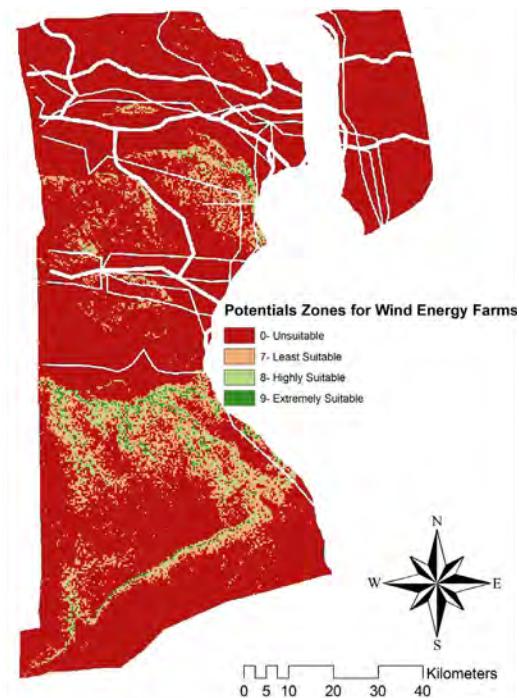


Figure 4. Suitability index for most appropriate zoning of wind farms in Suez Governorate

The results show that the central area of the governorate of investigated region has high wind energy potentials. These zones are proper for locating electricity generating wind turbines. The total exploration area is 53,083 sq. km. Total area classified into extremely suitable, highly suitable, least suitable, and unsuitable. The area of extremely suitable is 548 sq. km, highly suitable is 2002 sq. km, least suitable is 5387 sq. km, and unsuitable is 45145 sq. km. The results show that the Central region, North East, and South region of the Suez Governorate are the quietest rich in wind power potentials. There are some zones that have high suitability score, according to suitability map of wind farms in Figure 4.

### **Conclusion**

The awareness of using wind energy production has increased that as a clean alternative to non-renewable energy. This paper used the land suitability analysis conducted by the geographical information systems (GIS), in which multi criteria could be used to identify the appropriate locations of wind farms in Suez Governorate, Egypt. Different variables affecting the presence of wind farms could be added and overlaid in GIS including wind speed maps, wind directions map, and topography maps. The criteria depended on physical and socio-economic factors to find suitable lands to locate wind farms including the population density, land use, slopes, distance to roads, wind speed and transmission lines. The factors also include ecological purpose that not to be located near cities and airports. The results showed that 548 and 2002 square kms of the total area were extremely suitable and highly suitable respectively. The central and northeast parts of Suez Governorate of Egypt have showed to be the most suitable locations for wind farms development.

### **Acknowledgment**

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## References

- Funds, C. I. (2005), Emissions gases in Egypt. Cairo: Climate Investment Funds.
- May, S. (2014), What Is Climate Change? Nasa. Retrieved from <http://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-isclimate-change-k4.html>
- Baban& Parry, (2001). Developing and Applying a GIS Assisted Approach to Locating Wind Farms in the UK, Renewable Energy, Vol. 24, pp. 59-71.
- Chiras, (2010), Environmental Science, Jones & Bartlett Learning, 2010
- Nextra Energy Canada (2011), Conestogo Wind Farm, Revised Construction Plan Report. NextraEnergyCanada, Conestogo Project,
- Bartnicki, N. et Williamson, M. (2012). An Integrated GIS Approach to Wind Power Site Selection in Huron County, Ontario. Department of Geography, University of Guelph, Guelph.
- Moiloa, B.H.E. (2009). Geographical Information Systems for Strategic Wind Energy Site Selection. M.Sc. Thesis, Faculty of Earth and Life Sciences, Vrije University, Amsterdam.
- DEADP, (2006). Strategic Initiative to Introduce Commercial Land Based Wind Energy Development to the Western Cape: Towards a Regional Methodology for Wind Energy Site Selection, Report Series 1-7. Department of Environmental Affairs and Development Planning, Cape Town.
- CNdV Africa Planning and Design (2006). Strategic Initiative to Introduce Commercial Land Based Wind Energy Development to the Western Cape. Towards a Regional Methodology to Wind Energy Site Selection. Report 2. Methodology 1. Prepared for Provincial Government Wind Energy Landscapes: Specialist Study: Report 2. Methodology 1, 9-11.
- Luo, C. et Banakar, H. et Shen, B. et Ooi, B.T. (2007). Strategies to Smooth Wind Power Fluctuations of Wind Turbine Generator. IEEE Transactions on Energy Conversion, 22, 341-349.
- Bennui, A. et Rattanamanee, P. et Puettapai boon, U. et Phukpattaranont, P. et Chetpattananondh, K. (2007) Site Selection for Large Wind Turbines Using GIS. PSU-UNS International Conference on Engineering and Environment-ICEE- 2007, Phuket, May 10-11, 2007, 90112.
- Effat, H.A. et Hegazy, M.N, (2013). A Multidisciplinary Approach to Mapping Potential Urban Development Zones in Sinai Peninsula, Egypt, using Remote Sensing and GIS. Journal of Geographic Information System, 5, 567-583
- Effat, H.A, (2014). Resource-Based Zoning Map for Sustainable Industrial Development in North Sinai using Remote Sensing and Multicriteria Evaluation. International Journal of Sustainable Development and Planning, 9, 119-134.
- Saaty, (1980). The Analytic hierarchy Process, McGraw-Hill, New York.
- Janke, J.R, (2010). Multicriteria GIS modeling of wind and solar farms in Colorado. Renewable Energy, 35, 2228–2234
- Rodman, L.C et Meentemeyer, R.K, (2006). A geographic analysis of wind turbine placement in Northern California. Energy Policy 2006, 34, 2137–2149.
- Van Haaren, R.V. et Fthenakis, V, (2011). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. Renew. Sustain. Energy Rev. 2011, 15, 3332–3340.
- Van Hoesen, J. et Letendre, S, (2010). Evaluating potential renewable energy resources in Poultney, Vermont: A GIS-based approach to supporting rural community energy planning. Renew. Energy 2010, 35, 2114–2122
- Yue, C.D. et Wang, S.S, (2006). GIS-based evaluation of multifarious local renewable energy sources: A case study of the Chigu area of southwestern Taiwan. Energy Policy 2006, 34, 730–742.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Community Energy Schemes: The Role of Public Participation and Engagement

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**Abstract:** Faced by global challenges brought on by climate-change and over-reliance on fossil fuels, more people are looking towards developing energy systems characterised by renewables. Community energy groups have been identified as key stakeholders who could play a strategic role in enabling the transition to a clean and affordable energy supply. Acting as a contact for local energy consumers they can help residents engage with energy matters by harnessing local natural resources to build social capital, creating revenue to address community needs and combating fuel poverty. As these groups are defined by the communities in which they exist, public participation and engagement is vital to their success. The extent of community involvement could include identifying needs, generating solutions, seeking funding and managing assets to enable positive socio-economic impacts. In this paper, the authors examine how a community energy group in Nottingham adopted a model of local energy generation and storage to improve their energy security and to reduce fuel poverty. Results indicate that the use of various engagement strategies provides opportunities to encourage active discussions, explain processes and gather feedback. The regular planning of these sessions helps to maintain momentum, enthusiasm and commitment and encourage wider participation as the project progresses.

**Keywords:** Community energy, community engagement, fuel poverty.

### Introduction

Globally, there is a growing shift towards sustainable development to tackle heavy dependence on finite natural resources. Due to fossil fuels contributions to global warming and environmental pollution, a reduction in their use is marked as one of the key targets of the sustainability movement (United Nations, 2015). So far, major efforts have involved the setting of global low-carbon goals such as the Paris agreement of December 2015 which aims to undertake ambitious efforts to combat climate-change and adapt to its effects (United Nations, 2017). Even so, the success of this and similar global goals depends on their regional, national and local implementation. In the European Union (EU), the Renewable Energy Directive was established to create a policy that would require the EU to fulfil at least 20% of its energy needs with renewables by 2020 through the implementation of individual national targets. As part of this and other national initiatives, the United Kingdom (UK) aims to achieve a national target of 15% by 2020 (Department of Energy and Climate Change, 2010, p.5). With the onset of the UK's departure from the EU (Prime Minister's Office, 2017), it is anticipated that the government and other stakeholders will continue to be supportive of long-term global, regional and national energy goals that enable the development of an independent and sustainable energy sector. One of the most effective ways of doing this could involve enhancing the UK's energy policy agenda for energy security through the development of resilient local energy systems.

In this paper, the term 'community energy' refers to the collective action of purchasing, managing and generating energy for the benefit of the local community (Good Energy, 2016, Department of Energy and Climate Change, 2015). For a while now, community energy schemes have been advocated as being potential sources of innovation to support local sustainable energy transitions (Hargreaves et al., 2013, Barrett et al., 2010). This growing interest in community energy schemes has been driven by the view that they can be used to tackle energy-related issues from a local needs-based perspective and with wider national implications - such as in meeting the aforementioned low-carbon targets. Generally, the potential benefits of community energy initiatives include: improving energy security by reducing reliance on non-renewables, tackling climate change through decarbonisation and delivering economic gains by reducing energy bills (Department of Energy and Climate Change, 2015, Haggett et al., 2013). In addition to these benefits, community energy schemes can also deliver wider socio-economic outcomes for communities including increasing community resilience and cohesion and generating income for communities (Department of Energy and Climate Change, 2015).

Whereas the growth of community energy schemes has been substantial in other EU countries such as Germany and Denmark, their uptake has been significantly lower in the UK (The British Academy, 2016). This is attributed to the centralised nature of UK energy markets coupled by inconsistent government policy. Despite the fact that the UK government recently launched a community energy strategy in 2014 as a means of defining the pathway towards mainstreaming community energy (Department of Energy and Climate Change, 2014b), the financial linchpin for many community energy groups – Feed-in Tariffs (FITs) - were drastically reduced in 2016 (Community Energy England, 2016). The FITs scheme provided a guaranteed revenue stream for generators of small-scale renewables thereby allowing them to present themselves as successful business models that go beyond proving basic energy and monetary savings. At this time, perhaps drawing from the inherent resilience of the UK's community energy grassroots movement (The British Academy, 2016), there is the need for innovative methods that will continue to encourage the growth of community energy schemes. Indeed, successes realised in Scotland show that community energy can be instrumental in achieving broader public acceptance of renewables and in reaching national targets while stimulating local economies (Ministry of Business Energy and Tourism, 2015).

Increasingly, communities are becoming more engaged in energy markets as a means to securing a sustainable energy future (Good Energy, 2016, Haggett et al., 2013, Ministry of Business Energy and Tourism, 2015). With reference to a community energy group in Nottingham, the authors examine how public participation and engagement in the context of community energy initiatives can be used to unite communities to act on energy challenges and opportunities that are specific to their local area, while increasing knowledge, understanding and awareness of energy issues in general. Enablers and barriers to improving participation in energy projects are also discussed.

### **The Case Study Background**

The Meadows is an urban area with a population of approximately 9,000 residents located to the south of the city centre of Nottingham, UK (Nottingham City Council, 2013). The majority of the housing stock in the Meadows consists of large areas of social housing, and a core of traditional Victorian terrace houses (Nottingham City Council, 2010). Although the area has a long history of economic deprivation and fuel poverty, there is a tight community structure with a high level of community cohesion. In 2004, a study was commissioned by the

Nottingham City Council (NCC) to examine how the Meadows area could be revitalised to promote community resilience and improve the quality of life for residents by providing useful links to the city. Building on the findings of this study, a project entitled 'Ozone' was initiated to determine how the area could be transformed into the first low-carbon inner city area in the UK as a way of boosting the pride of the local community. With support from the Meadows Partnership Trust, the Nottingham Energy Partnership, the NCC, and local design and energy professionals, an area wide energy plan was developed in collaboration with community members. This initiative was entered for a national competition and won £250,000 to develop the ideas contained within it. As part of the development of this project, extensive community engagement was undertaken by way of public meetings, focus groups and forums where many local people helped to prepare the final bid for a prize of £25million. Building a foundation underpinned by active participation and strong social capital, this endeavour was very successful in motivating and engaging local people.

Although Ozone did not win the overall prize, it left the community with a feasible low-carbon blueprint. Keen to take this plan forward, community members obtained a grant to commission a study into the formation of a local energy services company (ESCO). Faced by rising energy prices, growing inflation and the impact of global warming, members of the community wanted to take control of their local situation for the betterment of their community. This eventually led to the formation of a local ESCO, the Meadows Ozone Energy Services (MOZES). So far, MOZES has recorded a significant number of achievements in the Meadows including: giving free energy advice to over 300 households, installing photo-voltaic (PV) solar panels on houses, providing zero-interest green loans, facilitating housing fabric improvements, holding energy workshops for local people and planning environmental talks for children in local schools. Other community engagement initiatives included setting up stalls at the local events and the introduction of the local MP as an 'Energy man' to champion and encourage energy saving and generation schemes.

The aforementioned engagement processes were particularly useful in promoting the largest initiative of the early years where MOZES was awarded government funding to carry out a means-tested solar PV installation programme as part of the drive to establish the Meadows as a low-carbon community. On the whole this programme led to the fitting of 65 PV installations on domestic properties (consisting mainly of social housing or low-income owner occupied housing), three schools and two community properties. Currently, only 11 PVs previously installed by MOZES at their own cost are eligible for FITs. Unfortunately, following the significant reduction of FITs by the government for PV panels installed post-2011, MOZES has been unable to generate income from the PVs installed as part of this scheme. Even so, in the spirit of community resilience, MOZES and its community members have endeavoured to seek other innovative ways of meeting its energy goals.

Currently, through the EU Horizon 2020 Project SENSIBLE (Storage Enabled Sustainable Energy for Buildings and Communities) running from 2015 to 2018, MOZES is exploring a local supply and energy storage model for community energy (Figure 1). Project SENSIBLE has three demonstration sites including Évora in Portugal, Nuremberg in Germany and Nottingham in the UK. Given the significant number of solar PV installations (including those installed by Nottingham City Homes and private homeowners), the varied housing types and tenures, coupled by the character of the local grid and the strength of the local community organisations, the Meadows area was found suitable for the Nottingham Demonstrator. The focus of SENSIBLE in Nottingham is to examine storage integration in buildings and communities, combining local renewable energy generation and energy-market participation.

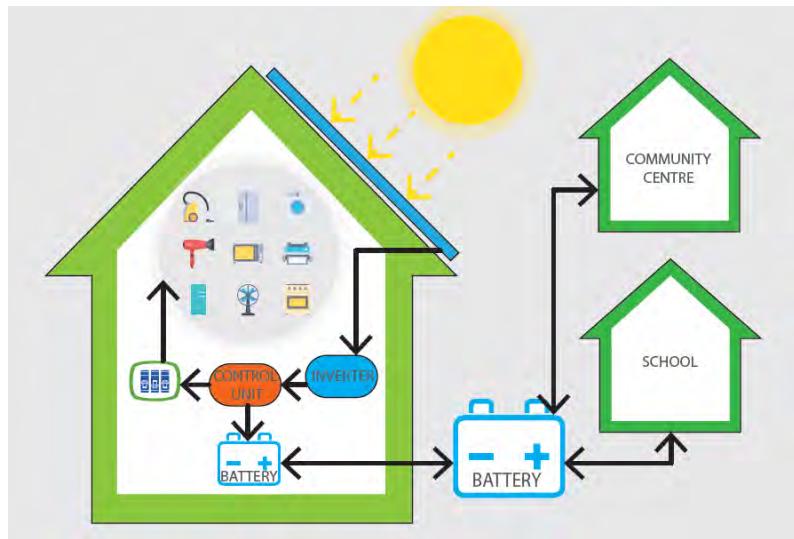


Figure 1. Community Energy at the Meadows in Nottingham

## Results and Discussion

In the development of community energy projects, public participation and engagement is useful for decision making, relationship development and capacity building (Community Places, 2014). In Project SENSIBLE in the Meadows, community engagement is treated as a cumulative process that aims to not only gauge the level of support for the scheme but also seeks to prioritise local needs, strengthen the relationship with the community, and review and inform on the project. Tailoring this process and keeping it open and transparent has meant that it started off easily and in a participatory manner. Using existing community networks and forms of communication to publicise these events and identifying opportunities to align to and hold combined events - as was the case when MOZES held its regular meetings and open days - facilitated greater engagement impact. As communities often need support to engage meaningfully (Community Places, 2014), the backing received from a pre-existing community group such as MOZES has meant that the project has found it easier to gain trust and support from the local community members.

The engagement strategy was divided into 3 separate components based on the identified use cases (Figure 2). The first consists of a domestic component where volunteer residents have one of four different versions of energy storage technology installed at their respective houses. The second is a community building - a school with variable seasonal use but with a large array of PV's already installed. The third is a housing development where there is an opportunity to install a private network for 10 houses. As the domestic component involved different house types, there was the need to match suitable technologies for each property. In order to complete the installation of the storage and monitoring equipment in good time (to allow for monitoring and the collection of a year of seasonal readings), the process of selecting the volunteers of the domestic properties was started in June 2015 and the final choices made in December 2016. With fewer factors to consider, the installation at the community school was simpler to arrange. The community battery planned for the development of 10 houses has suffered delays brought on by ownership and planning issues and has been exacerbated by the economic uncertainty brought on by the Brexit vote. Talks are still underway to chart the way forward.

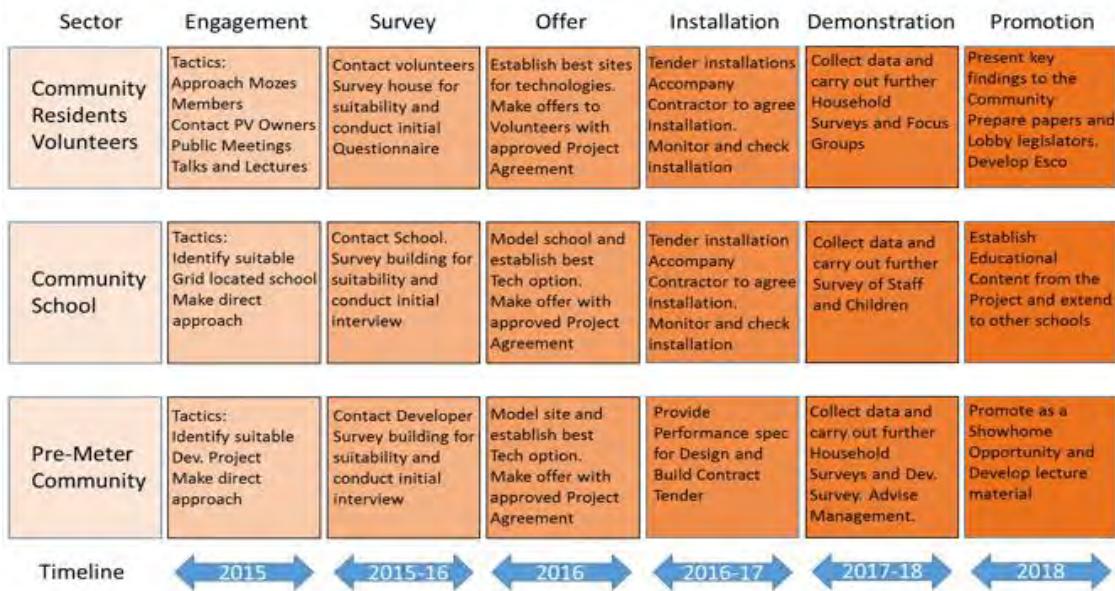


Figure 2. The Meadows Community Engagement Plan

Having previously engaged with Meadow's residents, including local champions of community energy, researchers from the University of Nottingham (UoN) were able to build on this rapport to promote open communication, develop trust and foster the community's participation in Project SENSIBLE. This process was initiated early with general and targeted canvassing. An initial public meeting was arranged and advertised via a flyer posted to residents and a mention made in the local magazine, Meadows Matters. As part of the targeted canvassing efforts, letters were sent to homeowners who had previously received PV's during the aforementioned solar PV installation programme and those who had shown an interest in energy savings in their homes. The letters introduced the proposed project and indicated that there would be more information available for interested parties. The initial meeting was well attended and a list of interested participants collated. Attendees were given presentations outlining how the project related to residents and the potential benefits. Also, case studies were presented to showcase similar projects in the EU and the UK.

A follow-up public meeting enabled the creation of a database of volunteer residents containing basic information about their properties. From November 2015 to February 2016, each household in the database was approached and their interest confirmed. Next, visits to these properties by a joint team from MOZES and UoN were conducted to explain the project in more detail and to answer any ensuing queries. During these visits, an initial physical survey was conducted of each property. In addition, the residents were requested to fill out a questionnaire that aimed to investigate the socio-economic and occupancy characteristics of the households and to examine community attitudes towards community energy, energy storage and Project SENSIBLE in general. From this, initial target lists of houses were drawn up to give a reasonable spread of house type, tenure, socio-economic group, storage type suitability and location in relation to the grid. Using this information, initial costs estimates for the equipment required were prepared to generate an approximate working budget to ensure affordability before any formal offers were made to individual residents.

Next, offer letters that detailed the storage and monitoring equipment and outlined the terms of installation were given to residents. Following the tendering of the installation work, the selected contractor carried out more detailed surveys of the designated properties. For this, the contractor also took full sized templates of the batteries, inverters and monitoring

boxes – these turned out to be much bigger than previously expected. Consequently, some houses were found unsuitable and were replaced by those on a reserve list. As the running of the project is long and intrusive, involving alterations to houses, it was decided after seeking views within the community to offer the batteries and monitoring equipment to householders at the end of the study period as a reward for their participation. To keep participants engaged outside of group events MOZES will mentor and monitor them through the remainder of the project. Already the installation process has begun with two trial installations being used to obtain general approval from the distribution network operator (DNO) and to iron out any other unforeseen issues. Following the installation process, participants will be contacted to establish if they are happy with the installation and to receive any immediate feedback. The collection of more detailed feedback on the entire project is planned. This will be followed by the presentation of study findings to the community.

The use of visible demonstrations through the provision of full-sized equipment templates gave interested participants a clear idea of their likely spatial intrusiveness. Although this led to the withdrawal of a small number of participants, it also gave those that went ahead sufficient confidence to get involved in the project with full knowledge of how the equipment would impact on their properties. To fill out gaps identified in previous forums, participants were taken through the monitoring equipment which would enable them to further engage with the project by viewing a selection of variables including: property PV generation, stored energy and energy savings. This was found to be quite useful given that the findings of the socio-economic study indicated that 65% of the respondents frequently monitor their energy use as a means of improving their energy efficiency and reducing costs. Following the completion of the project, it is anticipated that there will be a chance to open up selected homes to allow other community members to have a look at how storage works and how it benefits household occupants and the community at large. It is thought that this could go a long way in changing the attitudes of community members who have not been convinced about the benefits of integrating energy storage and PVs.

The socio-economic questionnaire was administered to households who confirmed their interest in Project SENSIBLE. Response rates were high with 81% of the 55 households that were approached filling out the questionnaire (one representative per household). The questionnaire was divided into five sections including: views on climate change and energy efficiency, views on community initiatives and energy storage, energy generation, supply and use characterisation, property characterisations and preferences regarding Project SENSIBLE. The results indicated that 94% of the respondents believe that the actions of individual households influence the rate of climate change. In addition, 82% of respondents indicated that people should be made to reduce their energy consumption to diminish climate change and its effects. Respondents indicated that their main drivers for reduced energy consumption include: financial incentives for the adoption of renewable energy (96%), high energy costs (83%), tighter building regulations (83%), better labelling in appliances and equipment (79%), higher tariffs for high energy usage (77%) and environmental awareness (77%). Rising energy costs were identified as a major factor prompting respondents to reduce their energy consumption. In fact, only 30% of respondents were satisfied with the price they pay for their energy at the time of the study. Further 41% of respondents indicated that had been concerned about their inability to pay energy bills in the past and wanted to adopt energy efficiency strategies to protect themselves in the future.

The cost of implementing measures to improve energy efficiency were a significant factor in enabling respondents to follow through. 82% of respondents indicated that they

would be willing to invest in low cost measures (under £500) to make their properties more energy efficient. This proportion fell to 50% when considering investments higher than £500. Although there is limited available data on the cost effectiveness of community energy in the UK (Department of Energy and Climate Change, 2014a), there is a general consensus that barriers faced by individuals can be overcome in community energy groups due to economies of scale, and especially where renewable energy is concerned (Department of Energy and Climate Change, 2015, Department of Energy and Climate Change, 2014a, Gelmon, 2005). In this study, majority of the respondents believed that shared energy initiatives can help improve energy efficiency (97%), infrastructure resilience (90%), social cohesion (91%) and reduce energy costs for individual households (97%). 90% of the respondents would like to see their community manage their own energy use with 92% willing to share excess electricity with the community. Most people also believed that centralised energy storage within communities (89%) and energy storage within households (95%) can improve energy efficiency. A review of preferences regarding SENSIBLE indicated that 98% of respondents were happy to have energy storage equipment installed in their homes and 55% would prefer to check for real time feedback on their monitoring equipment. In resonance with their shared standpoint on individual climate liability, respondents stated that their main reasons for joining Project SENSIBLE are 'to be greener' and 'to prepare their household for the future' (Figure 3). A second questionnaire survey is planned for distribution in late 2017 after the implementation and running of the energy storage equipment. The objective of this survey is to collect data and responses to showcase the socio-economic impacts of a community energy business model that incorporates energy storage in households and in the community.

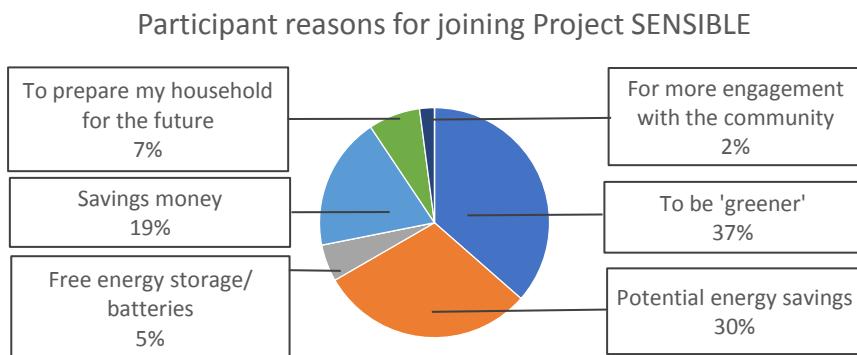


Figure 3. The Meadows Community Engagement Plan

By creating opportunities for dialogue, partners involved in SENSIBLE were able to present the potential benefits of energy storage in the particular context of the Meadows. This narrative positioned energy storage as a practical solution to local problems such as high fuel costs and fuel poverty, and possible contribution to wider regional and national objectives. The presentation of case studies gave community members clear examples of the successes and failures of similar community energy initiatives across the EU and in the UK. This gave community members a good idea of what is feasible through SENSIBLE and how it is likely to affect them on an individual and community scale. Often, unrealistic or unreasonable expectations are common in large innovative projects (Wall, 2012). To mitigate this and facilitate constructive engagement throughout the Project SENSIBLE's life-cycle, the managing of community expectations was initiated early-on and continues to carefully monitored. Partly as a result of this approach, community members appear to have

favourably compared the potential impact of energy storage in conjunction with the pre-existing PV's in their community with the alternatives.

## Conclusion

Community-led action can often tackle challenging local energy issues. This is attributed to their community relationship approach that enables them to be better placed than other actors to understand local areas and to bring people together with a common purpose. Meaningful engagement can be used to get participants involved by not only providing them with information on the project but by also enabling them to understand what is at stake and the problems that might arise. To overcome barriers to engagement, use of established community infrastructure is useful as it enables a wider reach. To avoid inefficiency in the engagement process, its purpose and scope should be designed and constantly reviewed to meet the intended project goals. Overall, engaged community members are less likely to perceive barriers to a local energy projects thereby enabling smoother project implementation.

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## References

- Barrett, M., Bradshaw, M., Froggatt, A., Mitchell, C., Parag, Y., Stirling, A., Watson, J. & Winzer, C. 2010. Energy security in a multi-polar world. *Energy Security in a Multipolar World*.
- Community Energy England 2016. Community Energy: The way forward.
- Community Places 2014. Community Planning Toolkit - Community Engagement. Community Places.
- Department of Energy and Climate Change 2010. National Renewable Energy Action Plan for the UK.
- Department of Energy and Climate Change 2014a. Community Energy in the UK: Part 2
- Department of Energy and Climate Change 2014b. Community Energy Strategy :Full Report.
- Department of Energy and Climate Change 2015. Community Energy.
- Gelman, S. B. S., S.D; Kauper-Brown, J.; Mikkelsen M., 2005. *Building Capacity for Community Engagement: Institutional Self-Assessment*, Community-Campus Partnerships for Health.
- Good Energy 2016. Good Energy Community Energy Report.
- Haggett, C., Creamer, E., Harnmeijer, J., Parsons, M. & Bomberg, E. 2013. *Community Energy in Scotland*, Edinburgh Centre for Carbon Innovation.
- Hargreaves, T., Hielscher, S., Seyfang, G. & Smith, A. 2013. Grassroots innovations in community energy: The role of intermediaries in niche development. *Global Environmental Change*, 23, 868-880.
- Ministry of Business Energy and Tourism 2015. Scottish Government Community Energy Policy Statement.
- Nottingham City Council 2010. Outline Business Case, Executive Summary, Meadows HRA Housing PFI. *Nottingham Insight*. Nottingham City Council.
- Nottingham City Council 2013. Census Community Profile -The Meadows. *Nottingham Insight*. Nottingham City Council.
- Prime Minister's Office. 2017. *Prime Minister's Commons statement on triggering Article 50* [Online]. Available: <https://www.gov.uk/government/speeches/prime-ministers-commons-statement-on-triggering-article-50> [Accessed 29th March 2017].
- The British Academy 2016. Cultures of Community Energy. London: The British Academy.
- United Nations 2015. The Role of Fossil Fuels in a Sustainable Energy System. *UN Chronicle*.
- United Nations. 2017. *The Paris Agreement* [Online]. UN. Available: [http://unfccc.int/paris\\_agreement/items/9444.php](http://unfccc.int/paris_agreement/items/9444.php) [Accessed 14th March 2017].
- Wall, C. 2012. Managing Community Expectations through Strategic Stakeholder Engagement. *International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*. Perth, Australia: Society of Petroleum Engineers.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Building Scenarios in Urban Energy Transition: A trans-disciplinary method for integrated spatial energy design

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**Abstract:** Within an energy transition process in the urban environment, a successful implementation of strategies requires the capacity of communities to develop and explore various visions and make decisions within an uncertain and complex context. To achieve a reduction of energy demand and to introduce technologies for production, storage and re-use of energy, different scenario types have been applied in energy and spatial planning in order to explore future pathways supporting and guiding decision makers. These are often used to compare the energy performance of different possible solutions and technological measures, underestimating physical and local spatial components to support integrated design processes, where spatial and energy urban systems can create a synergy for a better performance.

This paper describes the elaboration and the application of a transdisciplinary Design Oriented Scenarios (DOS) method for energy transition strategies, which is being developed within the framework of the JPI Urban Europe research project 'SPACERGY'. The DOS method, employed in the Hochschulquartier in Zurich, Switzerland, combines normative, descriptive and explorative components. It aims to help decision makers in a complex multi-actor process by setting common 'internal' transition objectives, sharing and creating a multidisciplinary common ground, and exploring alternative spatial and energy performative visions.

**Keywords:** Scenario, Living Lab, energy transition, urban design, Zurich

### Introduction

This paper develops a new methodology on scenario building within a Living Lab approach to achieve Energy Transition towards a low carbon urban environment. Scenario tools are already recurrently used in urban planning and design, in circumstances where it is important to take a long-term view of techno-social developments and related strategies. It is also useful when there are a limited number of key factors influencing appropriate strategies, and a high level of uncertainty about such influences (van Timmeren et al., 2011). Scenarios build plausible views of different possible futures for relevant actors based on groupings of certain key social, spatial and environmental influences and drivers of change. The result is a limited number of logically consistent yet different scenarios that can be considered alongside each other (*Ibid*).

Although in recent years scenario planning and scenario modelling have become more common (Schoemaker, 2004; Mehaffy, 2015), particularly in support of visioning processes (Lemp et all, 2008; Bartholomew 2005), a Living Lab Approach (LLA) implies the necessity of far-reaching interdisciplinary integration and active participation of the different actors. In the reconfiguration of urban areas, a number of actors is involved with different ideas of the future. What is needed, is a scenario based method that allows to set common objectives and

explore alternative future pathways, while helping the construction of common, so-called ‘desirable visions’. Despite a certain level of uncertainty, it can also be used in evaluating the effects of decisions taken.

To meet this demand, and the necessity for coordination of design, research and planning to realize a energy-sensitive approach in Energy Transition processes, a method is being developed in the JPI Urban Europe SPACERGY project for a main Living Lab, the Hochschulquartier in Zurich, Switzerland, alongside two other Living Labs in Bergen and Almere. The main objective of the SPACERGY project is the elaboration of new toolsets and guidelines to implement energy efficient urban development. Within the first analytical phase, the main goal was to identify social, political and economic components to determine potential trajectories for the development of the energy concept of the different study areas. Furthermore, the exploration of energy-spatial strategies to guide robust design choices and processes of implementation requires the creation of a solid and common knowledge basis. For these reasons, scenario building is considered as a ‘process related’ tool, with a triple role to explore and describe possible future conditions and to guide spatial-energy decisions to address the national and urban energy goals.

In the following sections, the new scenario method, which allows to define common visions within a multi-actor Living Lab (LL) approach, is described. In the first part the general framework is set, starting from different classifications of scenario types commonly used. Next, new scenario methods will be constructed in relation to energy transition objectives. In the last part the evaluation and testing in the Zurich LL, will serve to improve the theoretical basis as well as the developed method.

### **What type of Scenario model?**

Two fundamental definitions of scenarios can be distinguished, reflecting different epistemological views (van Notten et al. 2003; Rikkonen and Tapio 2009). The first is by Kahn & Wiener (1967) who define scenarios as built sequences of hypothetical events. The second is by Rothmans & van Asselt (1997) who see scenarios as descriptions of alternative images of the future, created from models that reflect different perspectives on the past, present and the future. According to these definitions, different types of scenario methods have been described in literature and applied in different contexts (Amara 1981, Borjeson et al. 2006, Dreborg 2004, Carsjens 2009, Sager-Klauß 2016).

In urban planning and design, scenario types can be classified according to content and objectives, as well as processes and methods. According to Manzini et al. (2008) a main distinction concerns Policy-Oriented Scenarios (POS) and Design Oriented Scenarios (DOS), where POS deals with the macro-scale and political decisions, and DOS are envisioned as tools in design processes. DOS, Manzini et al. claim, “should propose a variety of comparable visions to create inspiration for designers” and contain various proposals for a concrete plan, or a global vision which pictures the effect of the implementation, and which explains the main possible effects and general benefits, for example in terms of sustainability, economics, and social wellbeing. Another classification for types of scenarios regards the objectives on which these are built. According to Borjeson et al. (2006) scenarios are classified in three types : Predictive, Explorative and Normative. While predictive scenarios relate with the concepts of probability and likelihood, explorative scenarios have the aim to explore developments considered as possible to happen. Very often these take a starting point in the future, and are elaborated with a long time horizon to allow more profound changes. Concerning normative scenarios, the focus is transformed from visions into objectives and

the possibility to reach a certain target set. The interest in this case is on a desirable future situation and how this can be realised. Moreover, Rotmans et al.(2000) distinguish between normative (prescriptive) scenarios and descriptive scenarios. This last category describes, by using a deductive thinking process, how the future might unfold by applying known process dynamics or by similarities with other processes or experienced situations.

### ***Project objectives and selection of scenario type***

In the SPACERGY project, the selection of the type of scenario is based on the main objective: the building of a conceptual and methodological toolset to guide the design and urban development (including its technical systems) of the LL to achieve a successful energy transition. Although DOS are identified as useful tools to guide the process of design and identify visions in the specific context of urban transformations, these are often developed as a designed research product, without the involvement of stakeholders. In particular, concerning the field of energy planning and design, DOS have been associated with the visualization of energy footprint at larger scales, as explorative instruments, and for informing planning strategies. Therefore, in the context of Energy Transition towards a carbon free society, as Sager-Klauß (2016) states: "to start a process of energy transition in small and medium communities, guiding principles based on energy should be integrated in the urban development concept on a broad basis", while the process of envisioning should be developed by creating joint discussions with these communities and by including all relevant actors.

The main question thus became: What type of scenario model is needed in the Living Lab approach and how to improve the DOS approach for use in the LLs ?

Within the SPACERGY project the scope of scenarios intended as a tool is based on the aims:

- to collect knowledge by multi-disciplinary experts and actors and to understand drivers which influence the urban development (DESCRIPTIVE);
- to explore possible internal energy-spatial integrated development (EXPLORATIVE);
- to understand how to achieve national and urban objectives set for the energy-spatial transformation (NORMATIVE). For this reason, it is considered a hybrid DOS.

### ***Scenario based process design and method***

For the definition of a new framework for the hybrid DOS, following the scopes in a LL approach, the method merges in different phases characteristics of descriptive, explorative and normative scenario models in the procedural structure. Furthermore, the procedure inserts employment of techniques and activities which facilitate the interaction between scientific partners/researchers expert in different fields, together with municipality administrators as well as technicians. The scenario building itself is structured in three main phases, involving the following activities:

1) Preparation: i) Actors, energy policy, energy objectives and key drivers of change are identified, highlighting the role of planning instruments and main challenges and constraints for urban transformation. ii) A scenario matrix is developed taking in account the main factors of uncertainty.

2) Workshop: i) The scenario matrix is discussed and validated. ii) The participants divided in four heterogeneous groups describe and present the four visions according to the matrix. iii) The four visions are discussed for robustness and confronted

3) Evaluation and implementation: The multidisciplinary research team assesses the outcome, extrapolates the impact factors for a decisional and spatial integration, discuss the consistency, and plan possible modified implementation phases.

The resulting design scenarios will be assessed on their energy performance with a simulation model in a later stage (not described in this paper).

### Case Study in Zurich

The hybrid DOS, after a first application in the LLs of Bergen (N) and Almere (NL), has been improved and applied in the Zurich LL to the case study area of the 'Hochschulquartier' (HQ). The HQ represents one of the most important and challenging urban transformations within the city of Zurich. In the dense and central area, the transformation of the university district is meant to create an internationally competitive location for knowledge and health. Here, the interests and demands in terms of space, energy and transportation of three key stakeholders, ETH Zurich (ETH), the University of Zurich (UZH) and the University Hospital of Zurich (USZ) have to be considered and coordinated along with existing residential functions.

The transformation plan increases the usable floor space by 40%, and includes a variety of interventions: retrofitting the large existing building stock, building extensions, and the allocation of built volume on currently unused areas to increase the building density. Another key objective, which however might be more difficult to achieve, is to realize synergies and create a liveable urban district, exploring options to share the use of common functions and spaces (such as services, restaurants, cafeterias, housing etc.) and introduce new land use types.

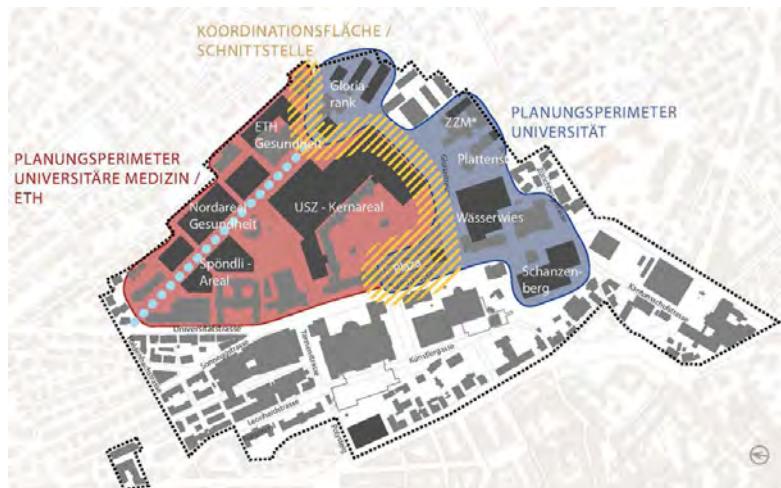


Figure 1. HQ Masterplan 2014. Hochschulgebiet Zurich-Zentrum Schlussbericht Vertiefungsthema Energieversorgung (2015)

These needs have to be balanced with the use of green spaces that are of great relevance for the area already, while the spatial transformation also has to go hand in hand with new energy solutions and set strict goals regarding energy performance. In this already challenging situation of high competition between different functions and their spatial use, the additional challenge is to meet the 2000 Watt Society urban goals. Furthermore, at the other (higher) administration levels, the energy policy commits to a challenging switch in the energy mix from nuclear power production to renewable energy generation by 2050. The HQ transformation takes this into account, although the potential to employ new energy sources and infrastructures has to be tied to a century-old distribution network as well. Besides, it

also needs to comply with the varying demands of the new developments in terms of quantity, quality (temperature) and dynamics.

A master plan approved in September 2014 (EBP, 2014) provides a first outline for renovating the structural and operational infrastructures of the site over the next 30 years. For the city of Zurich, the area represents not only one of the most challenging tasks in the near future but is also supposed to serve as an incubator and demonstrator for a new inclusive planning process that connects the relevant actors and leverages synergies. Due to its complexity, integration of spatial development, energy planning and mobility is crucial for the success of the transformation in the end.



Figure 3. View of the design project developed by Team Gigon / Guyer, in the design competition in 2015

#### ***First results of the hybrid DOS method applied in Zurich LL***

In this context of highly different interests and spatial competition, the development of scenarios is of fundamental importance to explore future options for the integration and tuning of energy and spatial measures. This section describes the results obtained by applying the hybrid DOS method to Zurich.

##### ***Development of a Scenario Matrix***

Based on a Scenario matrix (Figure 3), four Scenarios were developed. The 2x2 matrix is built on the two most critical aspects which impact the transformation in the HQ: (i) the composition of energy measures that can be applied in the area to buildings and to the urban fabric, and the degree of integration regarding both and (electric) mobility concepts; and (ii) mix in spatial functions and use, inversely related to the demand of transport in terms of number of trips.

The horizontal axis of the matrix relates to different spatial frameworks in terms of mixed functions and the levels of homogeneity/heterogeneity in the use of the public spaces. The consequence of multi-functionality directly affects the transport demand. The reason is that the availability of space for leisure, facilities, residential purposes and flexible use of the space of the campus 24/7 reduces the number of trips outside the area for the community. This dynamic is also valid for students/users that in the actual situation have to move to others clusters in the city to have the same utilities.

On the vertical axis, the scenario moves from a condition in which the different energy measures for generation, re-use and reduction of the demand are strongly integrated, to a less integrated portfolio of energy measures, where the supply is guaranteed by centralised

systems and infrastructures. These measures largely refer to the configuration and composition of the urban fabric and moreover to the integration of electric vehicles in the area for energy storage purposes and as an alternative for traditional transport solutions.

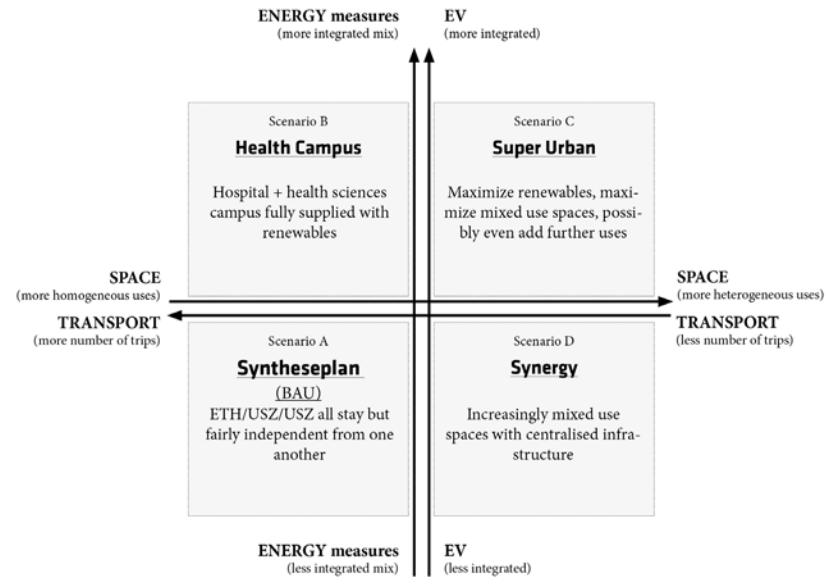


Figure 3. Scenarios matrix for the HQ

#### Description of the four scenarios

**Scenario 'Syntheseplan'(SP):** This scenario is based on the actual vision of the project for the HQ. The scenario depicts a future according to the prescription of a plan where the three institutions ETH, USZ, UZH separately develop their spatial plans, without any integration of uses. The assumption is that each of the institutions realises an extension, increasing the total built volume in the area. Regarding mobility, according to the new long term urban transportation planning, bike and pedestrian pathways are improved, while there are no relevant changes regarding car use. The amount of green spaces increases, however the nature of the area is not drastically changed, neither are they developed to proactively support outdoor comfort or microclimate conditions. The overall energy demand rises slightly. Regarding energy supply, the HQ is connected to the urban energy grid, linked to the existing energy power plants at the canton and national level. At the city level it consists of large system components and centralized infrastructures using waste heat from the main incinerator station and use of existing heat exchange potential from the river water. The only measures available to increase the energy performance in the area embrace the possibility of reducing energy demand by high-tech construction materials. Electricity demand is not covered by local or on-site generation.

**Scenario 'Health Campus'(HC):** This scenario is based on the tendency of homogeneity in use of the area where functions remain mixed but spatially clustered with a higher proportion of use related to health functions. At the same time, in the spatial transition, the HQ reduces its greenhouse gas emissions to the minimum, maximising the use of technologies to store energy generated by renewable sources, and using highly efficient distribution systems and building materials to diminish heat loss. Electric vehicles (EVs) are integrated in the local energy system. The total demand for transportation increases as the hospital attracts more users. Green spaces do not change in terms of footprint, but will be upgraded into more integrated and more shared high quality green spaces. In terms of functions, it is aimed for high integration of pedestrian and shared high quality green areas and increased

permeability of the area. Building functions are more integrated, with a focus on health. Energy demand is rising, but, in terms of energy supply, a mix of different sources and technologies for production is created. Focus is put on finding complementary functions to exchange excess heat. This scenario is considered the more extreme case, with the highest energy demand for the area, and where energy solutions in the hospital complex will be less dependent on existing energy infrastructures.

Scenario 'Super Urban'(SU): The SU vision embraces a synergistic mix of functional use and shared spaces during daytime, combined with a high mix of distributed energy solutions. This scenario implies further political decisions. Focus is put on multi-functionality and highly integrated and liveable solutions, with a combination of residential building, amenities and offices, optimized for balancing the energy demand. The aim is a 24/7 liveable area, which is pedestrian (and bike) friendly and has an increased overall accessibility. Thus, internal accessibility increases, while external accessibility focuses on its connection with the city centre, through public transportation, sharing of devices and dynamic services. Green spaces are multifunctional in use. As a result of multi-functionality and interaction, urban form is of increased importance, with emphasis on the building-street interface to achieve liveable public spaces. The urban form supports walkability in terms of street-scape quality and intervisibility. Energy demand is based on a high level of occupation focusing on demand reduction strategies, and complementary internal balancing in time. Energy supply builds upon reuse of waste flows at the level of the area, optimization of (distributed) renewable potentials, and thus including storage (matching demand and supply). Energy systems are integrated at the scale level of the area.

Scenario 'Synergy'(SY): The SY scenario builds on a mix of functions, where the main difference with SU is that the energy supply is more conventional with centralised infrastructures and less distributed sources. It focuses on a better functional integration of use compared to the SP, and less on energy supply, which employs renewable sources at a larger scale-level, with limited production in the area. As for transportation, focus is less on the integration of new solutions, and rather on improvement of existing public transport systems, and better tuning with pedestrian and bike-based mobility. Regarding energy demand the SY scenario builds on better integrated means to decrease the energy demand, and a functional mix to increase the overall effectiveness (joint energy footprint of mobility and use of space). Green spaces are multifunctional and well integrated with the built environment. Also in this vision, as a result of multifunctionality, characteristics of urban form such as compactness and connectivity play an important role to achieve spatial and energy integration.

## Discussion

A numerical analysis of the energy performance of the four descriptive/qualitative scenarios will be carried out in a second stage of the SPAGERCY research, providing the final assessment for comparison of the scenarios on a quantitative base. However, some preliminary conclusions can be drawn and factors of influence can be found by extrapolating the partial results presented in this paper.

The deductive construction of the four scenarios highlights the connections between the cooperation of types of land use and the availability of space for energy production. Where the integration of functions balances the energy demand, this also potentially decreases the competition for space. Furthermore, the introduction of microclimatic measures needs some more elaboration in the construction of a knowledge basis, since it seems there is little

awareness among the participants about the benefit from an energy perspective. Regarding mobility, a numerical model should distinguish between internal and external mobility both for mode of transport and calculation of the numbers of trips.

## Conclusions

The application of the DOS method has showed its capacity to support complex multi-actor process of spatial-energy transformation by helping in setting common transition objectives, sharing and creating a multidisciplinary common ground, and exploring alternative spatial and energy performative visions. In the evaluation phase of the method and its application in the Zurich LL, the four visions have been considered a fundamental contribution for the body of information and knowledge developed, and consistent in terms of description regarding the relations between the energy impact factors and processes. Quantitative indicators will be used in a second phase to calculate the balance between energy demand and on site production (normative value).

The authors and the other researchers involved in the process point out that the relatively limited number of actors that participated in the workshop can not be considered sufficiently representative. The difficulties regarding the involvement are related with a variety of cognitive limitations in dealing with uncertainty and complexity in scenario building, pointed out by Schoemaker (2005). In the case of Zurich, the high political sensitivity regarding the area, the request to discuss possible futures in a small setting and unusual framework in this context were the key elements that led to limited participation of the invited actors.

For this reason, a new phase has been planned to involve more stakeholders in the evaluation of the visions developed during the workshop by experts, making use of a interviews method. This additional implementation part in the hybrid DOS method is planned for the coming months, and aims to overcome the described shortcoming.

## References

- Aiger, C., Fenner, R. (2014). *Sustainable Infrastructure: Principles into Practice*. ICE publishing.
- Amara, R. (1981). *The futures field: searching for definitions and boundaries*. The Futurist, 15 (1), 25–29.
- Andersson  
Borjeson et al. (2006). *Scenario types and techniques: Towards a user's guide*. Futures.
- Carsjens, G. (2009). *Supporting strategic spatial planning: Planning support systems for the spatial planning of metropolitan landscapes*. Wageningen
- Dreborg, K.H. (2004). *Scenarios and Structural Uncertainty: Explorations in the Field of Sustainable Transport*. Stockholm: Royal Institute of Technology (KTH) Stockholm.
- Kahn, H., Wiener, A.J. (1967). *The Year 2000: A Framework for Speculation on the Next Thirty-Three Years*, Macmillan, New York.
- Lemp et al. (2008). *Visioning versus modelling*. Journal of Urban Planning and Development.
- Manzini, E. (2008). *Scenarios of sustainable ways of living*. Blog Ezio Manzini. Milano, 1-9.
- Mehaffy, M.W. (2015). *Urban form and Greenhouse Gas Emissions. Findings, strategies, and Design Decision Support Technologies*. A+BE | Architecture and the Built Environment
- Sager-Klauß, C.V. (2016). *Energetic Communities: Planning support for sustainable energy transition in small- and medium-sized communities*. A+BE | Architecture and the Built Environment
- Schoemaker, P.J.H. (2004). *Forecasting and scenarios planning. The challenges of Uncertainty and Complexity*
- van Notten, P.W.F., Rotmans, J. (2003). "An updated scenario typology." *Futures* 35(5): 423-443.
- van Timmeren, A., van Bauer, P., Silvester, S. (2011) *Smart Use of Storage Potentials of Electric Vehicles for Renewalbe Energy Generation in the Built Environment; a Design Scenario*, Proceedings World Conference Sustainable Building, Helsinki.



# PLEA 2017 EDINBURGH

*Design to Thrive*



## Assessing policy constraints and technical feasibility of energy developments in cities

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**Abstract:** GOMap (Geospatial Opportunity Map) was developed to support informed decisions concerning the siting of renewable energy systems in cities. It examined installing freestanding solar photovoltaic (PV) farms in Glasgow's Vacant and Derelict Land (VDL) and was implemented as an interactive Geographic Information System. In evaluating whether a site was suitable for renewable energy deployment, two sets of constraints were considered: technical factors which were imposed by the location on the achievable power level; policy factors which affected the likelihood of receiving planning permission. Two scoring methods were applied which generated different perceptions concerning the size of opportunity available, based on a 50x50 m grid across Glasgow. The stringent method applied the highest score for any individual layer as the combined score and resulted in 15.7 % of the VDL area as technically favourable and 7.8 % as politically possible; the recommended lenient method summed the individual factor scores and displayed 42.9 % as technically favourable and 46.8 % as politically possible. Focusing on the lenient method, it was found that 285 ha of suitable VDL could allow for 142,708 solar PV panels to be built, equating to an energy yield of 344.55 MWh/yr which could provide energy for ~70,000 dwellings.

**Keywords:** energy, renewables, geospatial, opportunity, map.

### Introduction

As part of the Future City Glasgow demonstrator project on Energy Efficiency (Energy Efficiency Demonstrator, 2017), Glasgow City Council (GCC) had chosen to develop a process for producing Opportunity Maps for urban renewable energy schemes. This was intended to be a concrete example of how technology could help make life in the city smarter, safer and more sustainable. Opportunity Maps would become publicly available tools which would help to identify land where community renewables projects could most easily be developed, and to give a guide to the kinds of challenges which might apply there; this should avoid wasted effort during the normal technical development and planning control stages of a project.

GOMap was developed to be a reusable method to estimate energy yields, evaluate potential constraints and have these displayed on an interactive map. The methodology was established through considering the potential for deploying renewable technologies on vacant and derelict land (VDL). This is land that at one time had been used for housing or industry, and so would be classed as a priority for being put to productive use; renewable energy generation is one – though not the only - possible use. Beyond the household level, the Scottish Government has set a target of 500 megawatts of community and locally-owned renewable energy to be deployed by 2020 (Scottish Government: Renewable Energy for Communities, 2013).

When evaluating the suitability of a site for renewable energy generation, two different sets of potential issues must be considered. The first is technical with the constraints imposed by the location on the achievable power level. Assuming these can be managed, the policy constraints that might constrain or facilitate the likelihood of receiving planning permission to build at that location need to be understood by potential developers. With multiple possible factors affecting each of the technical and policy issues, a critical aspect of the method is to weight each factor appropriately to give a realistic screening of the resource. In addition, technical and policy evaluations can conflict, so in order to understand options for management, it is important to be able to identify the specific issues at play in any one location.

Various published papers investigated the deployment of renewable technologies using GIS software, however most only focused on the technical/environmental aspect such as the predicted amount of wind/sunlight etc. in a given location or how much energy can be produced if a wind turbine/solar PV panel was built on a hill (Watson et al, 2015; Mekonnen et al, 2015; Mellino et al, 2014; Tiba et al, 2010). Although incredibly useful, they do not show a ‘realistic’ possibility in terms of the technologies actually being built but rather answer: *this is what you can get if it is built*. Few papers actually combine both the technical/environmental aspect **AND** those concerning the political constraints which are primarily dealt with by the decision makers themselves who have the knowledge and data of determining whether such a technology can be built, this can be the local/regional council or indeed the Government themselves (Asdrubali et al, 2013; Grassi et al, 2012; Juárez et al, 2014).

The aim of this project was to develop an opportunity mapping tool which could be used to determine the suitability of areas in which to deploy renewable technologies in cities. Glasgow (Scotland, UK) was chosen as the urban settlement for this project, the principal reason being that the city has received substantial investment in order to increase sustainability. Because of this, various technologies were being investigated in order to implement low-carbon renewable deployment. Glasgow was also deemed “the UK’s first green super city” ('All-Energy 2015 breaks records in Glasgow, Scotland', 2015). The renewable technology chosen for this project was solar Photovoltaic (PV).

Solar PV is most often deployed on roofs and integrated into the building’s electricity supply, with generation power constrained by the available surface area. It has advantages in a city context: it is not unsightly, and can be installed without disruption. However, it is a relatively expensive technology so it is important to understand how to make the best use of it to minimise costs and maximise income.

The tool was designed to take into account both the technical factors, which encompass renewable energy generation and their corresponding efficiency; and the policy factors, which can determine sites’ suitability. This tool, named “GOMap”, was built in conjunction with the free, open-source Geographic Information System (GIS) software – Quantum GIS (QGIS). It would allow decision makers and planners to create, edit, visualise, analyse and publish geospatial information in various formats. This allowed users to not only calculate optimal areas for renewable deployment but also visualise them with dynamic colour gradients. GOMap was used to investigate the installation of solar PV farms on vacant and derelict land.

## **Methodology**

A previous project examined developing an energy plan for the use of wind turbines in Caithness (Clarke et al, 1997). This procedure expands on the energy plan for Caithness and is summarised by the following points with focus on solar PV technology:

- Identified the factors which constrained power offtake or beneficial, economic return.
- Produced the base data to allow various areas to be effectively evaluated.
- Outlined the criteria where the policy and technical factors, at any location, would be assessed on a 3 or 4 point system.
- Scrutinised and allocated a score according to the data and criteria for a given location.
- Weighted and combined the individual factors which gave a combined score for both policy and technical factors.

For all policy-related data, a 4 score system was selected whereby each data layer was evaluated as one of '*Possible*', '*Intermediate*', '*Sensitive*' or '*Showstopper*'. The '*Showstopper*' score was used only in rare occasions where any kind of development would be deemed almost impossible, such as World Heritage Sites. For all technical-related data, a 3 score system was chosen whereby each data layer was evaluated as one of '*Favourable*', '*Likely*' and '*Unlikely*'. A 3 or 4 score system was chosen as it allowed planners to easily distinguish between areas where justifications of improvement can be done or not. Increasing the score system would only cause bigger ambiguity between the scores. For example, it is easier to process '*good*', '*medium*', '*bad*' than it is to process '*very good*, *good*, *medium*, *bad*, *very bad*'.

Each individual score was combined in order to deliver an overall evaluation for each of the policy and technical factors. Two scoring methods were formulated; each provided a different perspective, both mathematically and visually, of the area in question. These were known as the lenient and stringent methods:

- **Lenient (equal weighting):** This method summed up the scores for each set of constraints. This method provided the most realistic opportunity maps as it indicated where the high difficulty areas lie but also encouraged development as much as possible.
- **Stringent (user-defined weighting):** This method uses the highest score of any one factor as the combined overall score. In contrast to the lenient method, this provided the most pessimistic viewpoint in terms of opportunity available which ignored any possibilities of mitigation.

## ***Policy constraints***

Political constraints can greatly influence whether a renewable energy system can be developed on a site or not. Although many constraints can apply to most renewable technologies, some constraints are specifically tailored to address a particular energy system. For this thesis, the following factors were classified for freestanding solar PV:

- Environmental designation of land or buildings, such as sites containing special scientific interest.
- Land development zone such as housing.
- Glare which could constitute a safety risk to cars or aircraft.

- Possible presence of protected or endangered species, requiring surveys and mitigation plans.
- Visibility of the energy system from neighbouring housing.

### **Technical feasibility**

These factors were considered generic as they would have been associated with many different renewable technologies and were identified as to their influence regarding building and installing solar PV arrays:

- Distance to the nearest 11 kV substation on the grid.
- Capacity of the circuits in each 11 kV substation to absorb new renewables generation.
- Overshadowing from nearby buildings.

### **Data processing**

GOMap followed a strict procedure in order to calculate scores which determined how possible/impossible or likely/unlikely it was for a renewable technology such as solar PV farms to be built at a particular location based on specific constraints (e.g. conservation limitations, grid capacity etc.). To achieve this, a grid system at a pre-defined resolution was employed which covered the entire extent of the area.

Each polygon layer was *clipped* onto this grid and the resulting layer contained the exact same polygons broken up into grid cells with each cell becoming a polygon in itself. Therefore, if a layer overlaid another, their grid cells would also overlap perfectly. This overlap allowed for grid cells to be connected together which ultimately resulted in a single grid cell containing all of the overlapped data as shown in Figure 1.

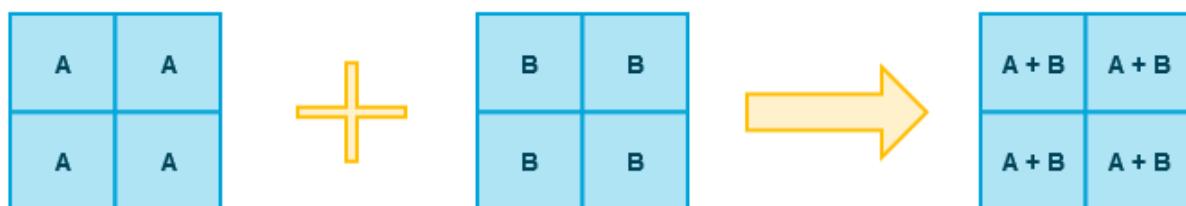


Figure 1. Grid system showing 2 sets of overlapping cells resulting in cells containing data from both.

### **GOMap**

QGIS was used to build the interactive tool, GOMap. Geospatial and attribute data are stored in shapefiles and become “layers” when imported into GOMap. Layers can be combined, filtered and used in calculations; in Figure 2, a colour coding was used to show the geographical variation in scoring - darker shades represent increasing levels of difficulty.

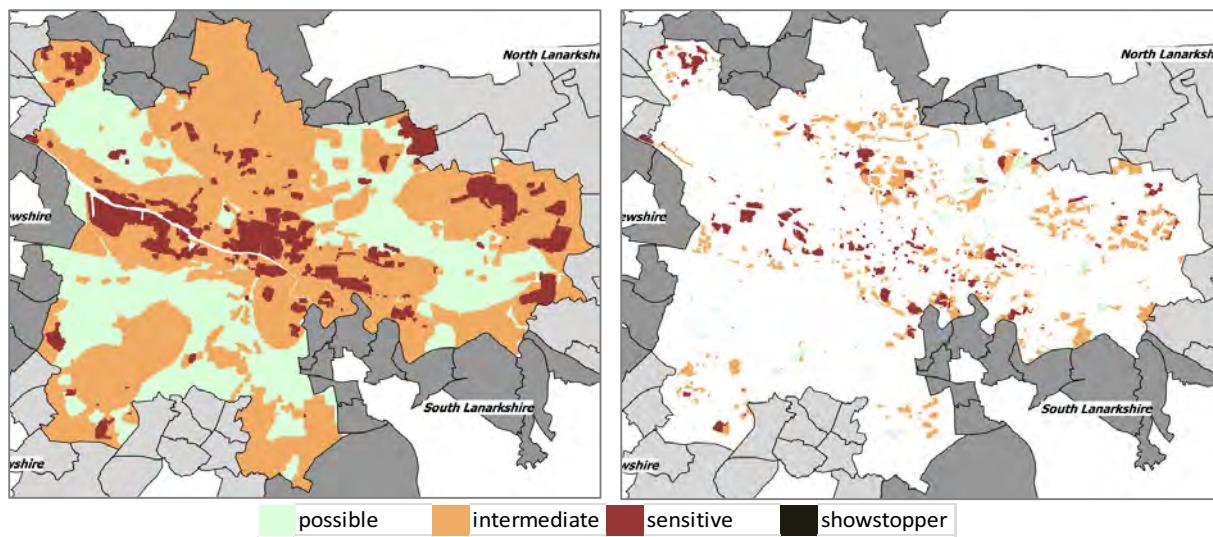


Figure 2. Layers showing development policy scoring across Glasgow and for VDL sites.

### Interface

GOMap provides a dynamic interface allowing users to continuously update the opportunity map in real-time by switching any constraint layer on or off. Acreage and energy yield statistics are calculated based on the selected constraints and reported to the user:

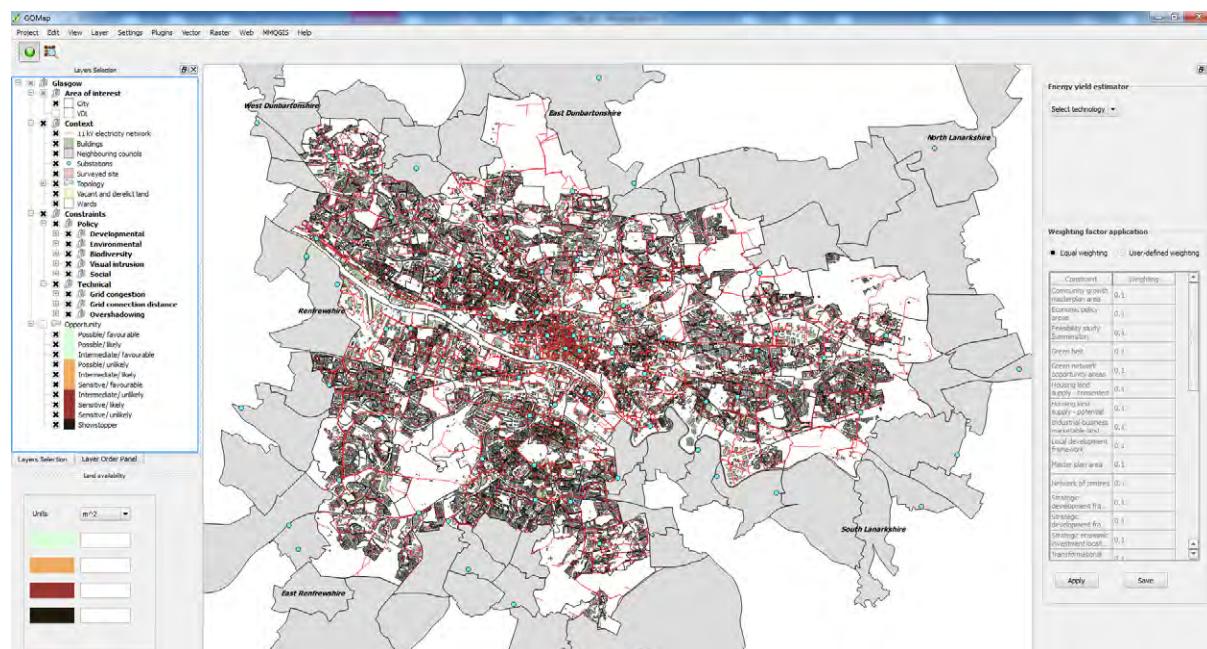


Figure 3. GOMap interface showing context layers for Glasgow.

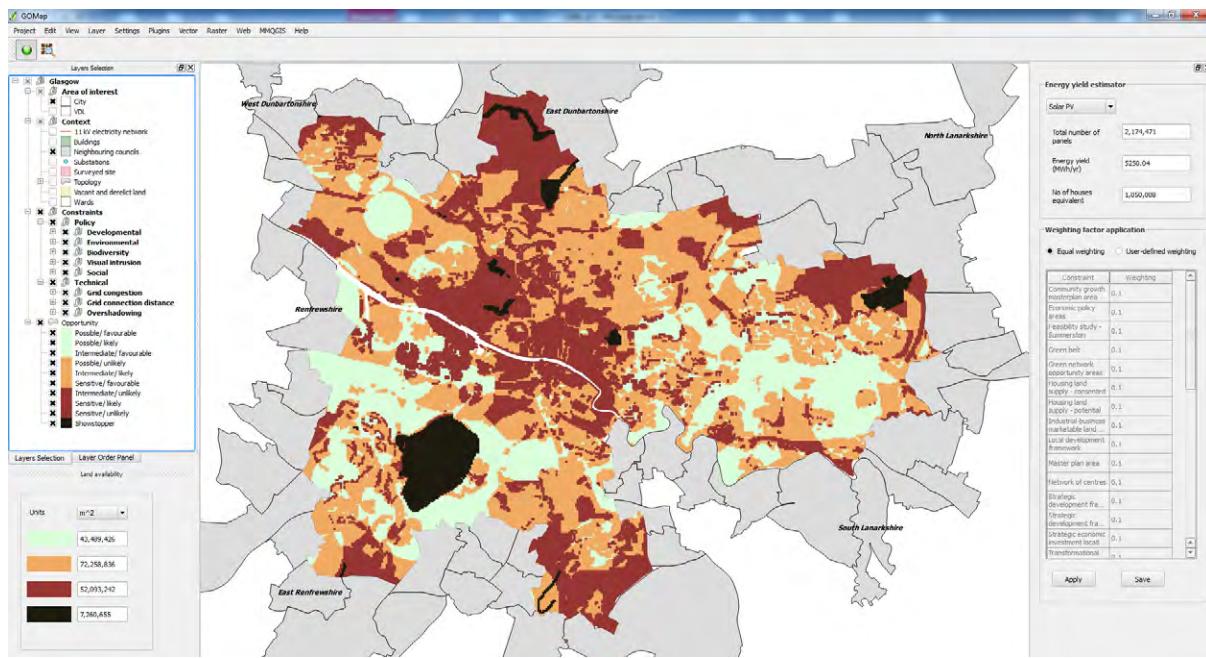


Figure 4. GOMap interface showing equal weighting opportunity for entire city.

## Results

GOMap calculated the land availability and solar energy yield for Glasgow in terms of both citywide (Figure 4) and vacant and derelict land (Figure 5). It was shown that the amount of land dictated as being possible for solar PV deployment was  $2.9 \times 10^6 \text{ m}^2$  or 285 ha. Using the lenient method and making the assumption that each solar panel has an area of  $20 \text{ m}^2$  and the energy yield for one panel is 3018 kWh/yr, then the total number of panels and annual energy yield were found to be 142,708 and 344.55 MWh/yr respectively. Assuming the average house in Scotland consumes 5000 kWh/yr, the number of houses that could be supplied energy from the solar panels equates to 68,910.

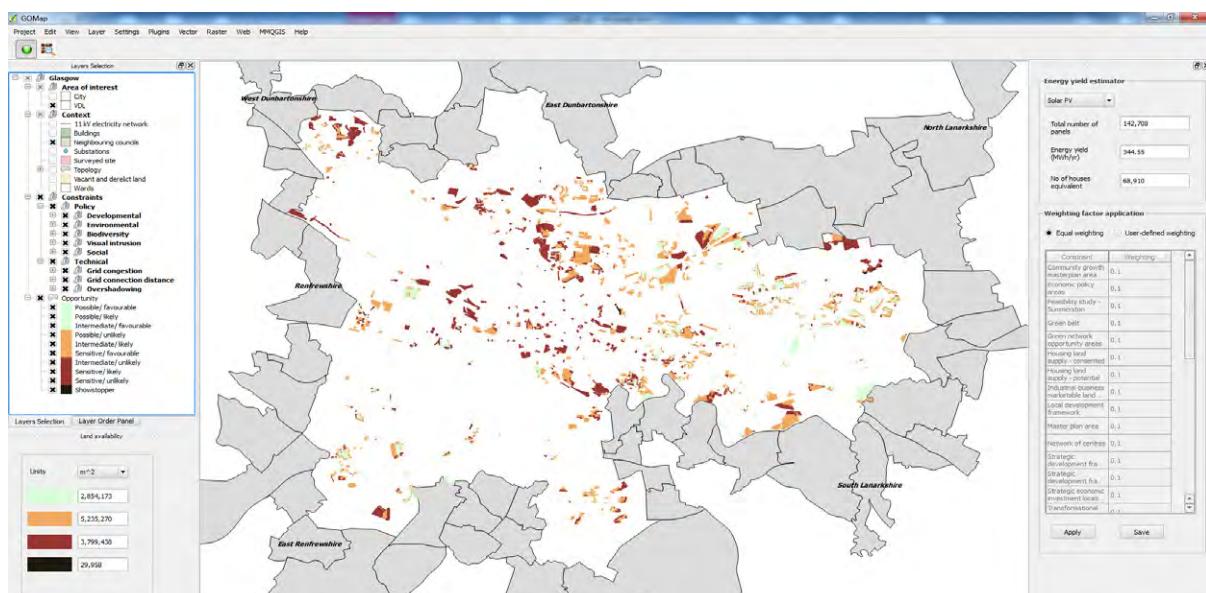


Figure 5. GOMap interface showing opportunity for vacant and derelict land.

The total area of vacant and derelict land in Glasgow was calculated as 1194 hectares. The calculations were performed using the area of each 50 m x 50 m grid square intersected by the VDL sites; this information was available in the attribute table for each grid cell. The deeper shades of colour indicated an increasing level of constraint. The main distinction in outcomes from using the different scoring methods can be seen in Table 1. When the lenient method was chosen, more land becomes readily available for renewable deployment in terms of both constraint types: with 46.8 % for policy and 43 % for technical. Conversely, the stringent method restricts much of the available land with only 7.8 % for policy and 15.7 % for technical. If the stringent scoring method was chosen, the level of difficulty appeared unpromising but alternative routes to bypass the apparent constraints may still exist.

Table 1. Comparison of proportion of VDL area scores by stringent and lenient methods.

	% VDL area	Stringent	Lenient
<b>Policy</b>			
Possible	7.8 %	46.8 %	
Intermediate	49.0 %	46.0 %	
Sensitive	42.9 %	6.9 %	
Showstopper	0.3 %	0.3 %	
<b>Technical</b>			
Favourable	15.7 %	43.0 %	
Likely	36.1 %	29.7 %	
Unlikely	48.2 %	27.5 %	

## Conclusion

GOMap has been developed to support informed decisions concerning the siting of community scale renewable energy systems. The tool was developed for freestanding solar photovoltaic (PV) farms in Glasgow's Vacant and Derelict Land (VDL). GOMap was designed to accommodate other energy systems in other geographies. The development process for this project involved close collaboration between the planning experts in GCC providing greater credibility to GOMap. It was implemented as an interactive Geographic Information System, running on a freely open source application, QGIS.

The tool illustrated how individual and combined scores could vary spatially across Glasgow, which would allow the user to examine overall suitability of a site in question and be able to extract detailed information. Each individual factor and combined score was displayed in layers all of which were based on a 50 x 50 m grid across the city. For some issues, data existed in order for it to be mapped across Glasgow while others required a detailed survey of individual sites.

Different combination methods were applied which generated different perceptions concerning the size of the opportunity available. The stringent method applied the highest score for any individual layer as the combined score and resulted in 15.7 % of the VDL area as technically favourable and 7.8 % as politically possible; the recommended lenient method summed the individual factor scores and displayed 42.9 % as technically favourable and 46.8 % as politically possible. Both methods could be used depending on whether the user

wishes to encourage maximum deployment of renewables or to minimise technology impact.

Regions of where the VDL areas are deemed politically possible and technically favourable were shown to have an accumulated area of 285 ha. As a result, 142,708 solar PV panels could be constructed with a potential annual energy yield of 344.55 MWh/yr, based on the assumptions discussed earlier. This could provide enough energy for just under 70,000 dwellings.

GOMap is an aid designed to calculate and provide opportunity maps for policy and decision makers and encourage collaboration with technology experts. GOMap can be transferable to other locations utilising other technologies. Technical constraints may be different for each technology but does not necessarily have to vary by location (i.e. the same technical constraints for solar PV in Glasgow could be applied to another city). However, each local authority or planning department will have their own approach to the policy constraints, so only the framework can be used elsewhere and appropriate evaluation criteria must be determined in each case. In other words, an opportunity map for Glasgow focusing on solar PV could have the same policy constraints as an opportunity map for Edinburgh focusing on CHP (combined heat and power) but the technical constraints may differ.

## References

- 'All-Energy 2015 breaks records in Glasgow, Scotland'. (2015). *Renewable Energy Focus*, 16(3), 4-4.
- Asdrubali, F., Presciutti, A., & Scrucca, F. (2013). 'Development of a greenhouse gas accounting GIS-based tool to support local policy making—application to an Italian municipality'. *Energy Policy*, 61, 587-594.
- Clarke, J. A., Evans, M. S., Grant, A. D., & Kelly, N. (1997). 'Simulation Tools for the Exploitation of Renewable Energy in the Built Environment: The EnTrack-GIS System'. *5th Conf. International Building Performance Simulation Association*. Prague.
- Energy Efficiency Demonstrator. (2017). Retrieved March 24, 2017, from Glasgow City Council: <http://futurecity.glasgow.gov.uk/energy/>
- Grassi, S., Chokani, N., & Reza , S. A. (2012). 'Large scale technical and economical assessment of wind energy potential with a GIS tool: Case study Iowa'. *Energy Policy*, 45, 73-85.
- Juárez, A. A., Araújo, A. M., Rohatgi, J. S., & de Oliveira Filho, O. D. (2014). 'Development of the wind power in Brazil: Political, social and technical issues'. *Renewable and Sustainable Energy Reviews*, 39, 828-834.
- Mekonnen, A. D., & Gorsevski, P. V. (2015). 'A web-based participatory GIS (PGIS) for offshore wind farm suitability within Lake Erie, Ohio'. *Renewable and Sustainable Energy Reviews*, 41, 162-177.
- Mellino, S., Ripa, M., Zucaro, A., & Ulgiati, S. (2014). 'An energy-GIS approach to the evaluation of renewable resource flows: A case study of Campania Region, Italy'. *Ecological Modelling*, 271, 103-112.
- Scottish Government: Renewable Energy for Communities. (2013). Retrieved March 24, 2017, from Glasgow City Council: <http://www.scotland.gov.uk/Topics/Business-Industry/Energy/Energy-sources/19185/Communities>
- Tiba, C., Candeias, A. L., Fraidenraich, N., Barbosa, E. M., Neto, P. B., & Filho, J. B. (2010). 'A GIS-based decision support tool for renewable energy management and planning in semi-arid rural environments of northeast of Brazil'. *Renewable Energy*, 35(12), 2921-2932.
- Watson, J. J., & Hudson, M. (2015). 'Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation'. *Landscape and Urban Planning*, 138, 20-31.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Feasibility Study on Renewable Energy Use in the Island in the Seto Inland Sea

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**Abstract:** Islands in Japan have local declining problem due to the population decreasing and the aging. On the other hand, island in Seto Inland Sea have rich natural resources, mild climate, and vast farmland, so they have high potential for using renewable energy. This study compares the supply potential of renewable energy and the energy demands of the houses targeting Osakishimojima. On the supply side, as an energy potentials considered local characteristics, 4 types of energies are calculated by using GIS. On the demand side, the total heat and electric are calculated by estimating the heating load and cooling load, and lighting and consumer electronics load and hot-water load by using simulation tools. Based on these result, the energy potential in target area is clarified, and the feasibility of Zero Energy Island (ZEI) is evaluated. As a result, the following were revealed. 1) In the target island, solar energy has high potential due to mild climate with many sunny days. 2) Comparing biomass energy, potential of the pruned branches is higher because of vast orchard. 3) The potential of renewable energy exceed the energy demands by combining the four types of energy in the target island. (ZEI is feasible)

**Keywords:** Renewable energy, Potential evaluation, Islands, GIS

### Introduction

In many islands of Japan, the population decreasing and the aging are progressing, and they cause various problems. On the other hand, the islands of the Seto Inland Sea have rich natural resources such as forests, mild climate, and vast farmland, so they have high potential for using renewable energy. Therefore, this study estimates the energy demands of the houses in the island and the supply potential of renewable energy and compares them targeting Osakishimojima located in the Seto Inland Sea (Kure City, Hiroshima Prefecture). Based on the results, this study also evaluates the feasibility of energy independence.

### Research outline

#### *Flow of this study*

The steps of this study are as follow.

- 1) Estimation of energy demands in the island
- 2) Estimation of the supply potentials of renewable energy
- 3) Evaluation of the renewable energy use potential.

In the following sections, these methods and results are described.

### **Target area**

For this study, Osakishimojima located in the Seto Inland Sea is selected as a target area. Figure 1 shows the map of Osakishimojima. This island has the problems caused by the population decreasing and the aging, such as a decrease of community, inconvenience of daily life, increase of low-used or no-used land, and so on. On the other hand, it belongs to the Seto Inland Sea Type Climate with mild climate and low rainfall, and fruit cultivation is active utilizing such climate and steep terrain. In this study, 4 types of renewable energies are selected as effective sources considering local characteristics of the target area, and supply potential by the energy sources are calculated (Table 1).

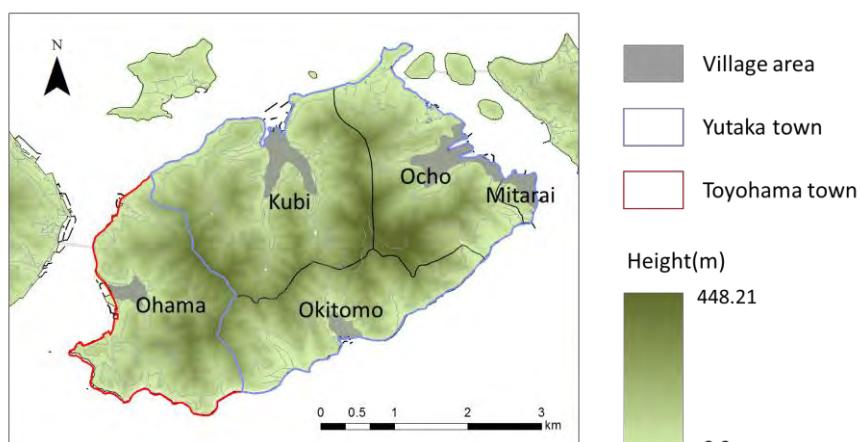


Figure 1. The map of Osakishimojima

Table 1. Local characteristics and renewable energy

Local characteristics	Renewable energy considered to be effective
The proximity of satoyama and living area	Woody biomass energy by forest utilization
Fruit cultivation is active	Woody biomass energy by pruning branches
Long sunshine hours	Solar energy
Having steep terrain	Small hydropower generation

### **Estimation of energy demands in the island**

This study estimates the unit values of energy consumption per house, and estimate energy demand across the island by multiplying the unit value with the number of households. For setting the unit value, weighted mean is taken in consideration of the ratio of household attributes. The calculation method of each the unit is shown below.

#### ***Lighting and home appliance electricity load and hot water supply heat load per unit***

Since the average number of persons in a household in the target area is 1.78, the basic unit is calculated for one-person household and two-person household. Here, as for family attribute, the percentage of households is set with reference to the population composition of Yutakamachi (Table 2). After that, a living schedule is created for each household size and family composition, and the basic unit value is calculated for each household using the Schedule Ver. 2 (Energy Simulation for Residential Housing Subcommittee, 2000). Finally, the basic unit value for the whole island is calculated by weighted mean. The results are shown in Table 4.

Table 2. Population composition by age and gender

Number of people	male	female
0-69 years old	496	443
70- years old	407	638

### ***Heating heat load and cooling electric load per unit***

Heating and cooling load are calculated using SMASH for Windows Ver. 2 (Institute for Building Environment and Energy Conservation, 2000). The number of households is similarly calculated for each household by 1 person / 2 persons. And it is assumed that the houses in the island are mixed in at the ratio referenced to the existing date as for the thermal insulation performance of the house, and calculations are made for each houses. The temperature obtained from the extended AMeDAS weather data are used as the weather conditions being inputted to the model (Architectural Institute of Japan, 2000). The results are shown in Table 4. The COP of cooling is set to 3 with reference to the previous study (Ozaki et al., 2014).

Table 3. Percentage of thermal insulation level

Thermal insulation level	
No insulation	55%
Old Energy Saving Standards	31%
New Energy Saving Standards	14%
Next Generation Energy Saving Standards	1%

Table 4. Each energy consumption rate

attribute	0-69 years old		70- years old		Weighted mean
	female	male	female	Male	
<b>Household by 1 person</b>	17.46		16.60		17.01
<b>Household by 2 person</b>	14.95	11.37	14.98	11.69	13.40
<b>Lighting and home appliance electricity load (GJ/house/year)</b>					16.14

attribute	male	female	Weighted mean
<b>Household by 1 person</b>	11.57		11.57
<b>Household by 2 person</b>	10.24	9.6	9.95
<b>hot water supply heat load (GJ/house/year)</b>			11.18

attribute	No insulation	old	new	next	Weighted mean
<b>Household by 1 person</b>	11.23	5.99	4.19	2.77	8.64
<b>Household by 2 person</b>	10.91	5.68	3.9	2.52	8.33
<b>Heating heat load (GJ/house/year)</b>					8.41

attribute	No insulation	old	new	next	Weighted mean
<b>Household by 1 person</b>	2.10	2.11	2.18	2.30	2.13
<b>Household by 2 person</b>	2.21	2.24	2.33	2.45	2.26
<b>Cooling electric load (GJ/house/year)</b>					2.23

### **Estimation of the supply potentials of renewable energy**

#### ***Woody biomass energy by forest utilization***

The supply potential of the broadleaf tree is calculated because it is the main tree type in the target forest. First, cutting plan is created considering multi functions of forest (water source

cultivation function and mountain disaster prevention function) using GIS. The created forest zoning is shown in Fig 2. Based on the zoning, authors set the clear cutting rate of each zone for the conservation of forest function. Specifically, based on the forest management plan, they are set 100% in the biomass production zone and 70% in the soil conservation zone and water source cultivation zone. Based on the rates, the annual available woody biomass quantity is calculated by the equation (1).

$$G_t = A/BC/DEF \quad (1)$$

As for the way for supplying woody biomass energy, assuming the case of using pellet stoves in which the all biomass energy is used for heat and the case of using gasification cogeneration in which the all biomass energy is used for heat and electric power, the supply potentials of each are estimated using equations (2), (3), (4).

$$W_{tp} = G_t H_t I \quad (2)$$

$$W_{th} = G_t H_t J \quad (3)$$

$$W_{te} = G_t H_t K * 0.8 \quad (4)$$

(0.8: Deduction of facility power usage)

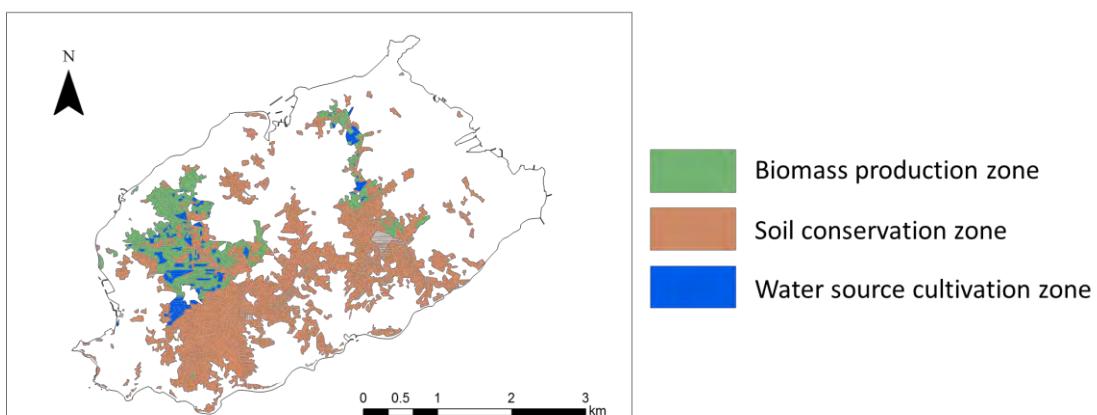


Figure 2. Forest zoning

### **Woody biomass energy by pruning branches**

In this island, cultivation of mandarin orange is active. Then, annual available woody biomass amount by pruning branch discarded from the tree of the orchard is calculated by equation (5).

$$G_p = LM \quad (5)$$

As the waste matter rate of pruning branch, the value of oranges 4.1 (t/ha/year) is used which is the main cultivation type of the target area (Sano et al., 2003). As with forest utilization, the supply potentials of two case (heat utilization, heat utilization + power supply) are calculated (using equations (6), (7), (8)).

$$W_{pp} = G_p H_p I N \quad (6)$$

$$W_{ph} = G_p H_p J N \quad (7)$$

$$W_{pe} = G_p H_p K J N * 0.8 \quad (8)$$

(0.8: Deduction of facility power usage)

### **Solar energy**

Here, the potential of solar energy is estimated on the assumption that solar energy absorber and photovoltaic panels are put on the roof of houses. Annual solar radiation is calculated using solar radiation analysis tool of GIS for targeting each village (using DEM with spatial resolution of 10 m). Fig. 3 shows the results. In the Okitomo village located in the southern

part of the island, the average solar radiation is higher. Average solar radiation of optimum inclination angle is calculated by optimum inclination angle  $27.3^\circ$  in Hiroshima (Okino et al., 1993), and the supply potential of heat and electricity power per house for each area are estimated by using the equations (9) and (10) with using this value.

$$E_H = A_s H_{\theta a} * 3.6 / 1000 \quad (9)$$

$$E_S = A_s H_{\theta b} * 3.6 / 1000 \quad (10)$$

By multiplying this value by the number of households in each area and integrating them, the supply potential of heat and electric power throughout the target area are estimated.

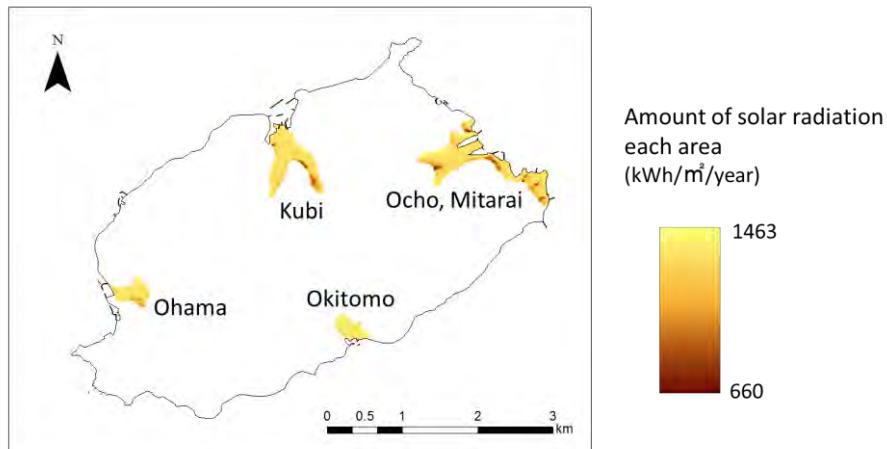


Figure 3. Solar radiation by each area

### ***Small hydropower generation***

A river is extracted using the hydrological analysis tool of GIS, and the flow rate and effective head difference are calculated. First, the power generation potentials at 10m intervals are calculated by using the equation (11).

$$P = 9.8 * Q H_c / 1000 \quad (11)$$

Then, 16 sites where the output is 20 kW or more are selected to set up the power generation facilities. Figure 4 shows 16 sites where a power generation output of 20 kW or more is expected. There is a tendency that effective sites are gathering in the upstream part of the Kubi area. The annual power generation potentials at these 16 sites are calculated by using the equation (12), and integrating them to estimate the electric power supply potential in the target area.

$$E_{pm} = P_d * 8640 * 3.6 / 1000 \quad (12)$$

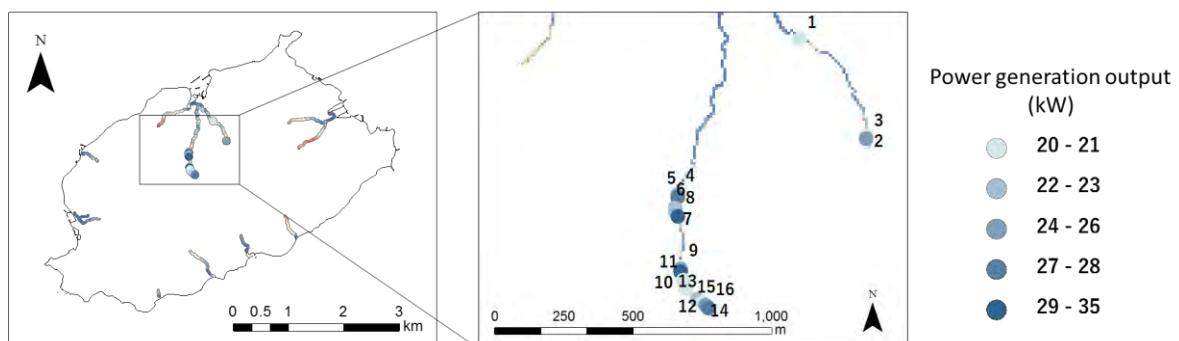


Figure 4. Sites where a power generation output is 20kW or more

## Evaluation of the renewable energy use potential

Fig. 6 shows total amount potential of renewable energy which is estimated in the previous section. Regarding woody biomass energy, there is a tendency that the supply potential of energy by pruning branches is higher than that of forest timber. Pruned branches are discarded in the process of fruit cultivations, so they are thought to be effective as an energy source in a target area where oranges cultivation is active. As a whole, the solar energy potential is higher both in the heat and the electric power supply potential. It is expected that solar energy is useful as an energy source in the Seto Inland Sea Type Climate which is mild and has many sunny days. As for small hydropower generation, it is possible to generate a certain amount of power generation by utilizing familiar agricultural canals.

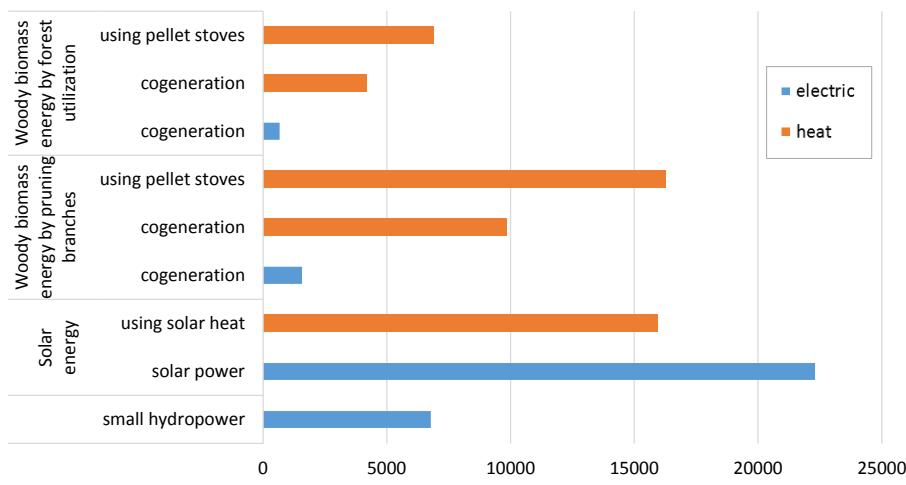


Figure 5. Total amount potential by renewable energy

Next, by using the results of this study, the supply potential of renewable energy and the energy demands are compared in the target area. As for woody biomass energy, there are two ways to use that are the pellet stove and gasification cogeneration. As a result of estimating the supply potential by the two cases, in either case the supply potential of both heat and electric power exceeds the energy demands and energy independence in the target area seems to be feasible. Considering that surplus electricity can be sold, it is preferable to supply by cogeneration for both thinned and pruned branches. Fig. 7 shows the supply-demand balance in the case of cogeneration of both thinned wood and pruned branch.

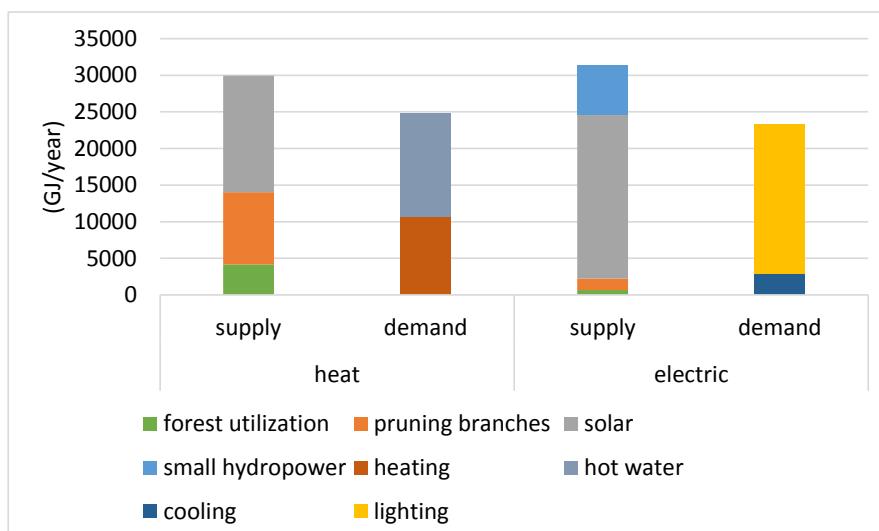


Figure 6. The supply-demand balance

## Conclusion

In this study, the energy demands and the supply potential by renewable energy are estimated targeting Osakishimojima located Seto Inland Sea. And comparing them, the feasibility of energy independence is evaluated. As a result, this island has high potential of renewable energy and independence is feasible. As future work, authors will also consider the economic aspects.

## Note

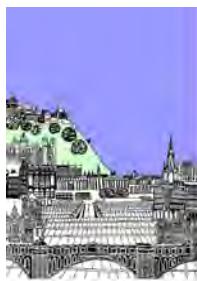
Table. 5 shows Nomenclature of equation (1) to (12).

Table 5. Nomenclature

$G_t$	Annual available woody biomass quantity by forest utilization (t/year)
A	Total forest area of the zone to be logged (ha)
B	The age of the forest to be cleared (years)
C	Forest volume of logging forest ( $m^3$ )
D	Forest area of logging forests (ha)
E	Cut clearance rate (%)
F	Dry specific gravity (0.6 t/ $m^3$ )
$W_{tp}$	Heat supply available amount by pellet stove (GJ/year)
$H_t$	Calorific value of hardwoods (18.017GJ/t)
I	Thermal efficiency of pellet stove (66%)
$W_{th}$	Heat supply available amount by cogeneration (GJ/year)
J	Thermal efficiency by gasification (40%)
$W_{te}$	Electric power supply available amount by cogeneration (GJ/year)
K	Power generation terminal efficiency (20%)
$G_p$	Annual available woody biomass quantity (t/year)
L	Orchard area (ha)
M	Pruned branch of oranges per unit of discharge (t/ha/year)
$W_{pp}$	Heat supply available amount by pellet stove (GJ / year)
$H_p$	Calorific value of pruned branch (7.95 GJ/t)
N	Availability rate of pruned branch (76.4%)
$W_{ph}$	Heat supply available amount by cogeneration (GJ / year)
$W_{pe}$	Electric power supply available amount by cogeneration (GJ/year)
$E_H$	Heat supply available by using solar heat (GJ/year/door)
$A_s$	Solar collector area ( $6 m^2$ )
$H_\theta$	Solar radiation at optimum tilt angle (kWh/year)
a	Heat collecting efficiency of solar heat (0.4)
$E_s$	Electricity supply potential by solar power generation (GJ/year/door)
b	Overall efficiency by solar power generation (0.084)
P	Power generation by small hydropower (kW)
Q	Flow rate ( $m^3/s$ )
H	Heading difference (m)
c	Overall efficiency of small hydropower generation (0.72)
$E_{pm}$	Annual power generation capacity (GJ / year)
D	Facility utilization of small hydropower generation (55%)

## References

- Architectural Institute of Japan (2000), *Extended AMeDAS Weather Data*, Architectural Institute of Japan.
- Institute for Building Environment and Energy Conservation (2000), *SMASH for Windows Ver.2: Program for Heat Load Calculation for Residents*, Institute for Building Environment and Energy Conservation.
- Energy Simulation for Residential Housing Subcommittee (2000), *SCHEDULE Ver.2.0: Program for Automatic Creation of Life Schedule*, The Society of Heating, Air Conditioning and Sanitary Engineers of Japan.
- Ministry of the Environment (2001), *Reports on the Study Group on Formulation of Scenario for Greenhouse Gas Reduction Technique in 2000*, Ministry of the Environment.
- Sano, T. and Miura, S. (2003), "A Study on the Availability of Woody Biomass Energy according to area", *Proceedings of JSES/JWEA Joint Conference*, pp. 469-472.
- Okino, M., Miki, N. and Nishioka, M. (1993), "Suitable Direction of Photo-voltaic Cells for Solar Power Generation: Study by using of the Standard Weather Date", *The Society of Heating, Air-Conditioning Sanitary Engineers of Japan*, pp. 101-104.
- Ozaki, A., Inoue, G., Lee, M. and Ozaki, Y. (2014), "Future Prospects of The Household Energy Consumption: Scenario building of energy conservation for Hadano", *Journal of the Architectural Institute of Japan*, 79(700), pp. 489-497.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A Proposal of Comprehensive Urban Infrastructure Planning Model for Smart City Planning with GIS and 3D modelling - Case Study in Urban Area of Tokyo

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**Abstract:** Smart city has been becoming nowadays a common concept for sustainable city development under accelerated urbanization, through the optimal management of the resources and offering a comprehensive high quality life for the citizens. Especially Japan, one of the advanced countries facing the complex issues of an aging society, disaster management and fossil energy dependency promptly needs a new methodology for optimal urban energy planning to achieve environmental friendly city development. Comprehensive urban energy planning requires appropriate analysis and planning support mechanism along with the urban development proceeding. This paper proposes a comprehensive urban infrastructure planning model with an integration of geographic information system (GIS) and 3D modelling, which can offer the link between energy scenarios and urban development information by location support technology. Firstly, it introduces the concept and components of this tool with considering Japanese transit-oriented development as well as the architecture of the smartization. Secondly, several scenarios for implementing low carbon urban area are applied. Suggested scenarios include various energy conservation technologies for Net-zero energy buildings, decentralized and local renewable resource utilizations. Finally, comparison and comprehensive assessment are conducted for these scenarios, inconsideration of not only the energy conservation effect, but environmental effect and economic feasibility as well.

**Keywords:** Smart city, Geographic information system (GIS), Urban energy planning, Building information modelling (BIM)

### Introduction

Smart city has been becoming nowadays a popular topic that not only in developed countries but also in developing countries. There are a variety of definitions for smart city in different fields and regions. Generally, it aims for a sustainable city development through the optimal management of the resources and potential, offering a comprehensively high quality life to the citizens (I. Vassileva, 2016).

To deal with the environmental and energy problems caused by urbanization, the planning of area energy system is one of the most important issues. Rather than the high efficient energy system design in a single building, the urban energy planning needs to improve its existing system while putting forward new system in a cooperative way. The technologies or policies should be decided based on other related energy elements, like the city infrastructure (the energy supply from the generation to demand side), the distribution of natural energy potential (related to renewable energy) and urban structure (effect to demand side and infrastructure development). Instead of one single solution, urban energy technical packages, dealing with the environmental degradation should be an optimal approach, with synergies among various elements and energy solutions.

Especially for Japan, one of the countries facing the complex issues of an aging society, disaster management and energy dependency need a new methodologies for optimal urban energy planning that integrates all information from these sectors.

This paper proposes a comprehensive urban infrastructure planning model with integration of geographic information system (GIS) and 3D modelling, which can offer the link between energy scenarios and urban development information by using the supporting technology of local position information in an area. The model can set various scenarios and evaluate their energy conservation, environmental and economic effects under different urban development features. The urban area of Tokyo is adopted as case study to examine applicability of the model. Firstly, it introduces the architecture of proposed urban energy planning tool. Secondly, several scenarios for implementing low carbon urban area are applied. Suggested scenarios include various energy conservation technologies for Net-zero energy buildings, decentralized and local renewable resource utilizations. Finally, comparison and comprehensive assessment are conducted for these scenarios, inconsideration of not only the energy conservation effect, but environmental effect and economic feasibility as well.

### **Components and architecture of the tool**

Urban energy planning should comprehensively consider the factors both from urban planning and energy saving technologies. There are two concepts of urban planning for smart city development in Japan, compact development and layer integration (S. Yamamura, 2017). When a particular technology is deployed, the scales and sizes of its component must be sized and planned to suit all the infrastructure system.

This research proposes a GIS-BIM based urban energy planning tool to support the planning of smart cities. The integration of GIS and BIM can interpret the holistic city. The 3D building model built up by BIM is located on the city 3D model set up by GIS. The data of building level that related with energy performance are offered by BIM, while the infrastructure data of city level are offered by GIS. It is the base for energy demand prediction, which is input into the simulation process to test the effect of proposed energy policies and technologies. The result of the calculation for a single building is returned back to the city 3D model that supported by GIS. Comprehensive assessment both in the building and city level is adopted to get the optimal technology package.

Urban energy planning should be based on the information from the city level, offering various policy technology packages to the communities that are with different urban infrastructure conditions. It can be used by various kind of users. For one area energy planning project, the planner can get the urban plan information, the community features and the appropriate energy technology package by inputting the location of the target area. Further, the related urban infrastructure information can also be obtained for further optimal design, combining with other existing simulation software. The averaged users, energy management operators or government can use the 3D platform for the visualization of the energy consumption of the city, district or building.

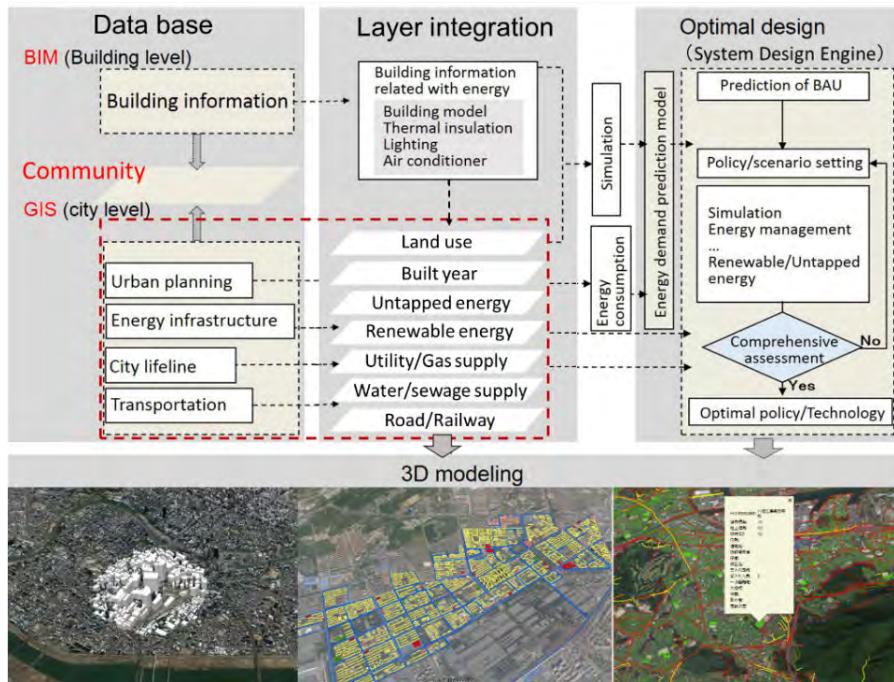


Figure 1 Structure of the tool

Figure 1 shows the architecture and components of the tool. It consists four parts: the database sector, layer integration sector, optimal design sector and 3D visualization sector.

Database sector and layer integration sector interpret the city information by layered data. The building information related to energy consumption are from BIM, and the other urban infrastructure data are offered by GIS. The simplified building big data from BIM are integrated with the city model that build by GIS. These sectors offer input data for optimal design sector and 3D visualization sector. The users can use the data for energy system optimization or directly visualize the existing condition of the community by 3D visualization sector.

Optimal design sector has the database of various technology packages for different types of community. By inputting the project location, it selects the optimal technology package by the community features offered by database sector. These data is processed into further simulation and analysis, selecting the optimal energy solution when it has a high environmental and economic performance.

Visualization sector adopts the 3D visualization in GIS and BIM to display the existing energy consumption, simulation result, facility operation and infrastructure condition. It can be developed into the user-friendly system that combines with web-GIS.

### **Case study of the communities around JR Yamanote line in Tokyo**

#### **Target area**

The communities around JR Yamanote line (one of the most important circular railway line) in the center of Tokyo are adopted as case study to suggest the different effect of the technologies in different area.

There are 29 stations for JR Yamanote line. Taking the station as center, the buildings within a radius of approximately 1000 meters in 12 TOD communities, which contains all the target building (do not overlap within other community) are selected as targets for case study (Figure 2). There are around 150,000 buildings in these 12 communities.

The building point data from urban planning which contains the information of location, building type, building area are used this research.



Figure 2 Target buildings around JR Yamanote line

### **Layered community features**

- Building scale

In the 12 communities, the total building area is around 156 billion m<sup>2</sup>. It is supposed that the buildings with more than 50,000m<sup>2</sup> are large scaled buildings (supposed to be the target of ZEB ready\* buildings). Only 28% of the building area is composed with large scaled buildings, the other 72% are small and medium scaled buildings. Figure 3 shows the distribution of the building area. It also suggests that only Tokyo, Shinjuku and Shinagawa station are occupied by over 40% rate of the large scale building.

\*ZEB ready in the case study refers to the buildings with advanced high low carbon technologies which realizes nearly zero energy consumption (over 50 - 60% energy reduction).

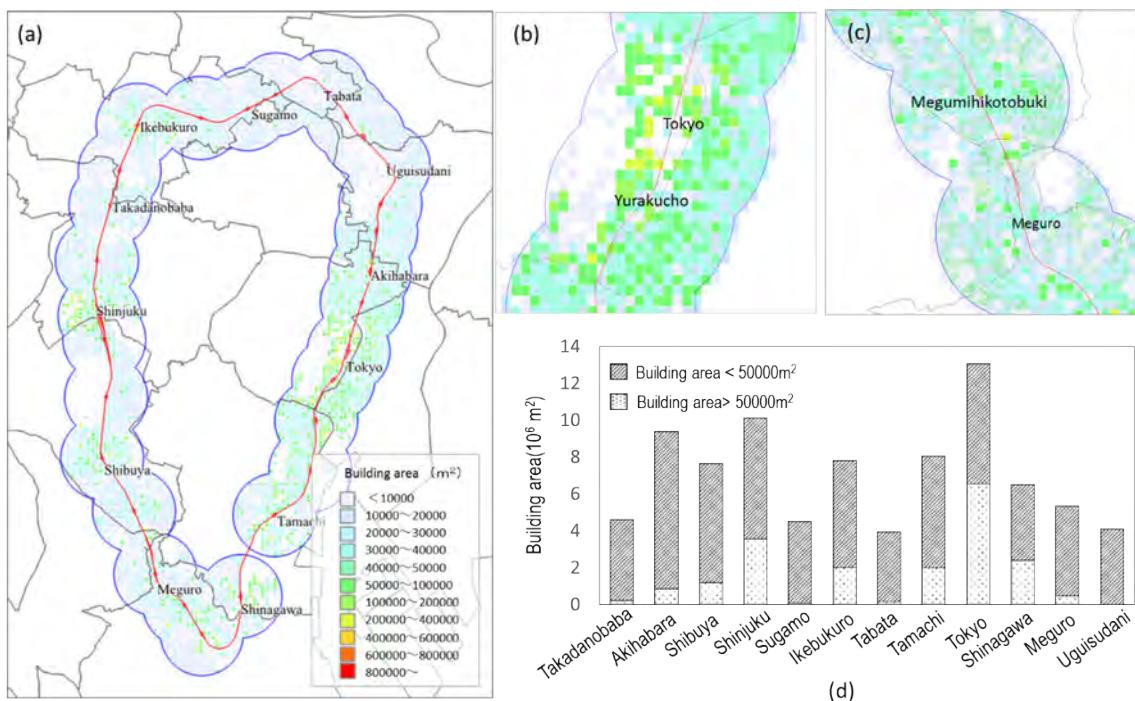


Figure 3 Building area distribution in target communities

#### - Building type

Figure 4 clarifies the constituent of building type. It suggests that the station with more large scaled buildings such like Tokyo, Shinagawa and Shibuya station have around 50% commercial or office buildings. Other communities have more residential buildings. Large building renovation like ZEB ready\* are difficult to be implemented in these residential areas.

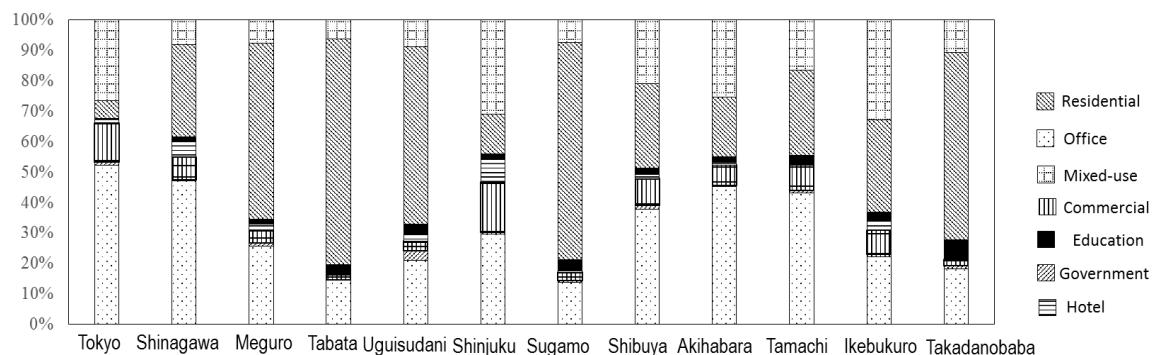


Figure 4 Building type in target communities

#### - Existing building energy consumption

In Japan, there is the Data-base for Energy Consumption of Commercial building (DECC) that reports yearly energy consumption unit, the energy consumption of every building types of building in per unit ( $m^2$ ) every year [<http://www.jsbc.or.jp/decc/>]\*\*. This energy consumption unit and building area are adopted for the estimating existing building energy consumption. It can be calculated as formula 1).

i : Building type

Ei: Yearly energy consumption for building type i

Si: Building area for building type i

**\*\*Commercial:4529, Office:1648, Residential:778, Mixed use:1600 MJ/m<sup>2</sup> year**

#### - Potential of solar power generation

In addition to the enough energy saving, the energy generation is sufficient for creating energy balanced communities. Especially from the ZEB ready\* standpoint, the potential of solar power generation is essential to realize the nearly zero energy buildings. Figure 5 shows the annual solar power generation on the difference roof sizes in the target communities. Most of solar power generation are from buildings with the roof size under 500m<sup>2</sup> except communities occupied by large scale buildings like Tokyo and Shinagawa area.

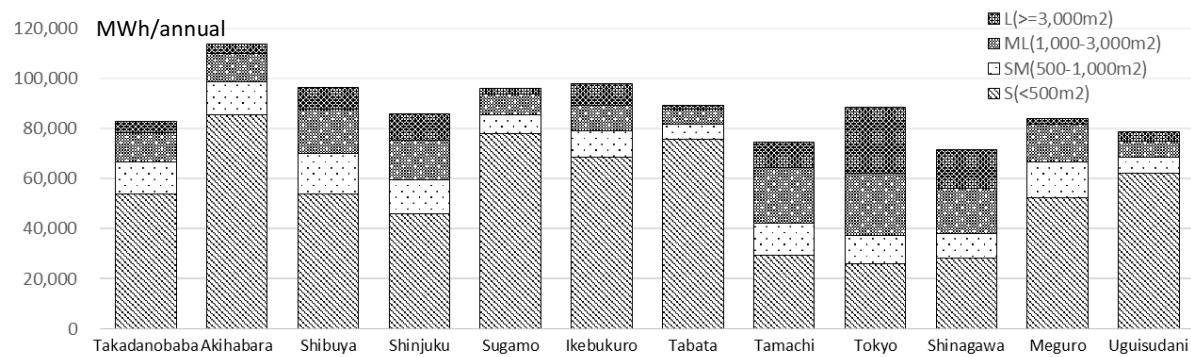


Figure 5 Potential of Annual Solar Power Generation in target communities

## Case setting

The ZEB ready\* building renovation tend to be limited in large scale building construction projects because they usually require the higher initial cost than the usual low energy buildings. This research suggests tentatively that ZEB ready\* can be only implemented in the buildings that with building area larger than 50,000m<sup>2</sup> (considered as the large-scale projects). Another method is a “long tail method” which means the large-scaled buildings works on high efficiency method (ZEB ready \*) while low cost energy saving method like an installation of LED, high efficiency air conditioner are supposed to be implemented in small and medium scaled buildings. This research sets three cases that are listed in Table 1 to compare the energy conservation effects of these communities.

Table 1 Case setting

Case	Energy conservation measures
Case1 Large-scale development priority model	Over 60% energy-reduction renovation (aiming ZEB ready*) in case over 50,000m <sup>2</sup> No additional measures in cases under 50,000m <sup>2</sup>
Case2 Long tail method1	Buildings over 50,000m <sup>2</sup> renewed to 20% energy-reduction Buildings under 50,000m <sup>2</sup> changed fluorescent (FL) lights to LED and use High efficiency air-conditioners (10% reduction)
Case3 Long tail method2	Buildings over 50,000m <sup>2</sup> renewed to 20% energy-reduction Buildings under 50,000m <sup>2</sup> exchanged FL lights to LED, use High efficiency air-conditioners and implement energy management (20% reduction)

## Results

### Energy saving effect comparison

Figure 6 shows the annual energy consumption and energy saving effect by the three cases shown as Table 1 in the target communities. The result suggests that large-scale development priority model (ZEB ready\* model) are more effective in the communities with more large buildings. In other communities and in the total of communities, the long tail method has better effect. This tool can visualize the distribution of the energy consumption status in each area in communities and this will be supportive to grasp the detailed energy saving effect from the district comparison standpoint (Figure 7).

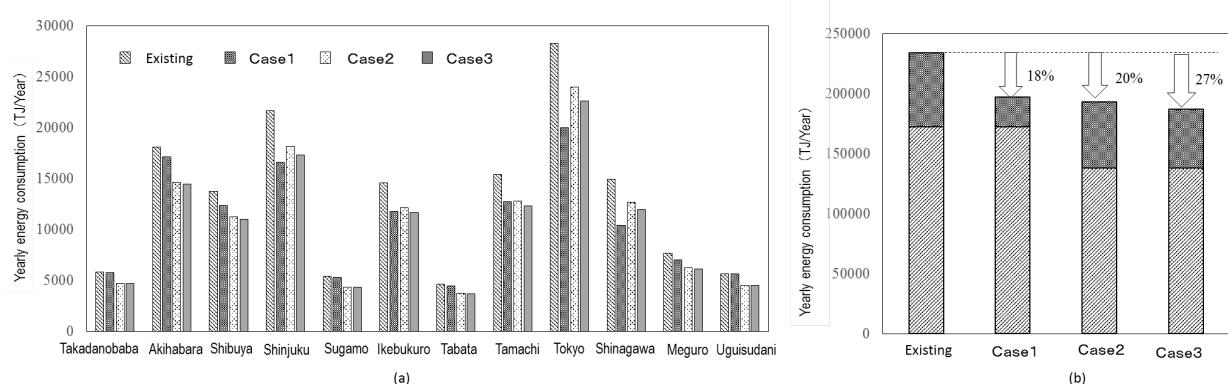


Figure 6 Annual energy consumption for target communities

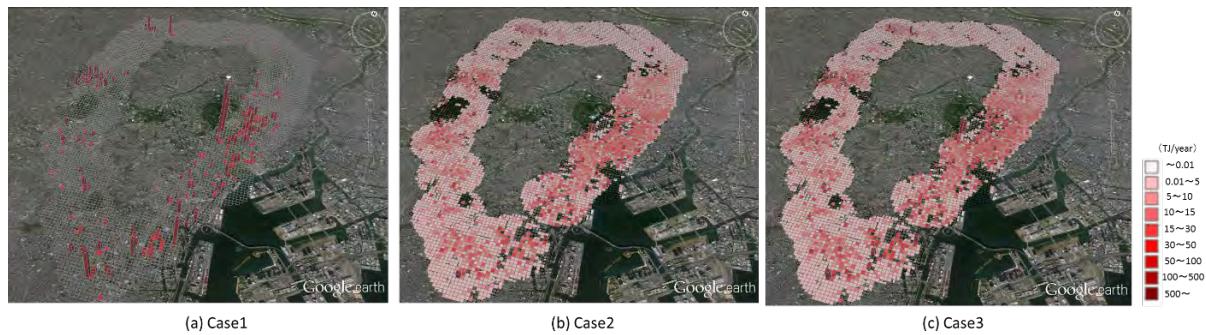


Figure 7 Distribution of annual energy conservation effect of cases

### Initial cost comparison

Adopting the optimized low energy methodologies that would be suitable for the characteristic of each building also should be considered from feasible point of view.

The comparison of initial cost increase in Figure 8 has been evaluated by using the calculation condition as shown in Table 2. In the condition of Table 2, the Long tail cases are considered more feasible than the case of aiming ZEB ready\*. But, the detailed comparison result in Figure 8 shows its feature that which case would be feasible between ZEB ready\* case and Long tail cases depends on the portion of large scale buildings and other smaller scale buildings in the target communities. The communities like Meguro, Tabata or Sugamo station area that are occupied by a lot of small buildings under 10,000m<sup>2</sup> of total floor would not be difficult to implement the ZEB ready\* project if there have several large scale buildings.

Table 2 calculation condition of initial cost for different technologies

Technologies	Unit initial cost increase from standard Bldg. (JPY(USD)/m <sup>2</sup> )
Energy-reduction renovation (aiming ZEB ready*)	19,140JPY(174USD)/m <sup>2</sup> (nearly equivalent to 7% cost up from standard building, 2017) ***
LED	190JPY(1.73USD)/m <sup>2</sup> ***
High efficiency air-conditioners	1,290JPY(11.7USD)/m <sup>2</sup> ***
Area Energy Management	250JPY(2.3USD)/m <sup>2</sup> ***

\*\*\*The initial cost increases were estimated with referring the related construction cost research report (The Study Report of Load Map for ZEB, 2015, Ministry of Energy, Trade and Industry (METI), Japan )

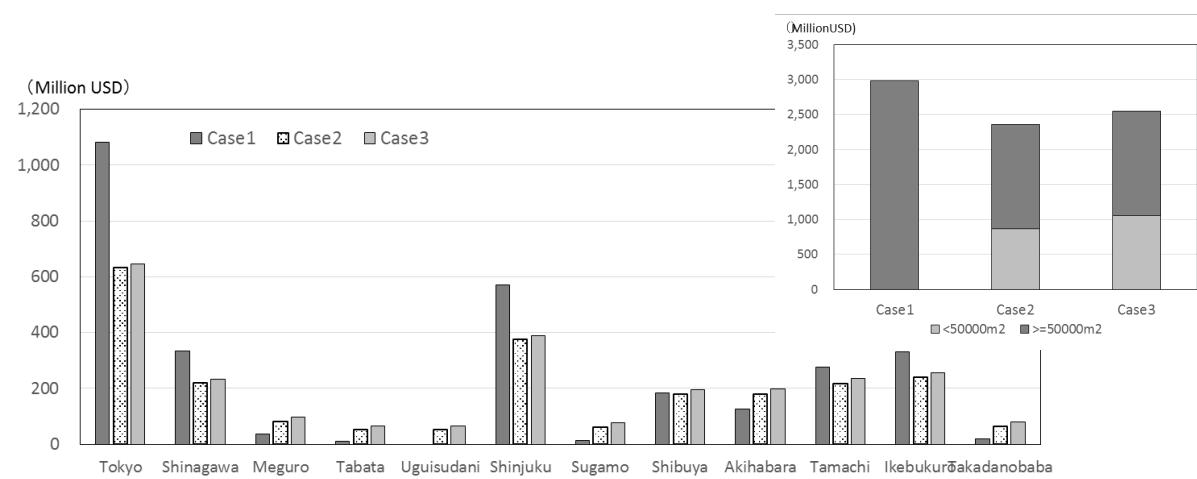


Figure 8 Comparison of Initial cost increase in different communities and cases

## **Discussion and conclusion**

For the future transition of urban structure and energy planning, municipalities and developers need a tool for solving different environmental issues across different scales. This study has suggested a GIS-BIM-based urban energy planning tool that is able to propose the appropriate solutions for a future smart city, and that considers urban development and infrastructure regeneration for future smart development. The proposed tool works as a multi-function system that can (a) combine GIS-based data and other data resources across a city, a community, or a building; (b) model the city with layered data integration; (c) predict and simulate the effect of energy conservation technologies on multiple scales as deployed by municipalities and developers; and (d) use 3D city modeling for visualization.

The primary results of the study are as follows:

(1) An overview of the urban energy planning tool, including its underlying development concept, architecture, and basic function, is provided. Collaborative modeling using GIS and BIM, taking communities as an immediate scale, unifies data across a city and for single buildings to support comprehensive analysis.

(2) The TOD-oriented communities around the stations of the JR Yamanote line in Tokyo, high potential areas for urban development, were adopted for case studies to evaluate the proposed tool's feasibility. In order to clarify the relationship between energy conservation effects and initial cost, the ZEB ready\* and long-tail methods were applied in the case studies.

(3) The advanced low-energy buildings, such as ZEB ready\*, can effectively reduce the large amount of energy consumption in certain buildings (i.e., large-scale buildings), but over a wide range of areas the long-tail method has shown the potential to realize a higher energy conservation effect. Therefore, using the proposed tool it is possible to determine which method can efficiently and economically reduce the energy consumption in a large area.

(4) The result also suggested that, for a city overall, various energy policies and technology packages in consideration of district-level features are required to realize the energy conservation at the community and city levels.

(5) Projects in developing or emerging countries do not always start under the appropriate economic and social conditions that would allow utilization of cutting-edge technologies or design methods that have been cultivated in more advanced countries. Thus, it is deemed necessary to propose schemes that combine advanced technologies with conventional methods that fit the local conditions of a project site. Therefore, the tool in this research is suited for developing or emerging countries.

The research described in this paper generally detailed the architecture of a tool with a first step in which the GIS is adopted for the necessary analysis the tool would perform. Future work will be aimed to develop middleware for GIS and BIM data integration, query, and visualization. More details of the enabling technologies and the cost performance should be analyzed, and an energy plan support system developed that would be made available to the related institutions as prospective users of the tool. Furthermore, for implementation of the tool in developing countries, additional research will focus on wider data collection, case studies, and the different and appropriate technology packages to these countries.

## **References**

- I. Vassileva, E. Dahlquist, J. Campillo, The citizens' role in energy smart city development, Energy Procedia 88 ( 2016 ) 200 – 204J.
- S. Yamamura, Assessment of urban energy performance through integration of BIM and GIS for smart city planning, Procedia Engineering, 2017

# Construction

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# PLEA 2017 EDINBURGH

*Design to Thrive*

## **Temporary Architecture: Proposal of a Temporary Educational Module for Public Institutions of Brazil Dedicated to the Education of Young People and Adults under the Optical Minimization of Energy Expenditure**

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**Abstract:** In the Brazilian building industry there is a common sense attitude to take any building demands as permanent, and to look for durable solutions, which are at the same time solid. Therefore, the most frequent solution for any building design problem adopts a structure of reinforced concrete and masonry skin and partitions. As a result, buildings are expensive and energy-intensive for being exaggeratedly solid. The dematerialization of buildings is therefore an opportune field of research. For presenting a probably decreasing demand along time, youth and adult education establishments were taken as a case study. After a decentralization policy promoted in Brazil with rapid expansion, beginning in 2000, several schools have been closed. A standard design solution adopted throughout the country was analyzed and compared to a temporary solution, developed according to the Design Science Research approach. Temporary or ephemeral buildings are better known in terms both of the durability of components and the end of life procedures, being thought for disassembling rather than demolition. A comparison in terms of energy life cycle shows that less durable buildings may be the most sustainable solution in the case of demand fluctuation, as observed in the youth and adult education in Brazil.

**Keywords:** Temporary architecture, energy Performance, energy Lifecycle.

### **Introduction**

According to data from the Demographic Census / IBGE (Brazilian Institute of Geography and Statistics), in recent years, an illiteracy rate among people over the age of 15 has been reduced in Brazil, from 13.6% in 2000 to 8.7% in 2012 (IBGE, 2017). Although the pace is lower if compared to that of previous decades, a significant discrepancy between the values of illiteracy in the rural environment and the urban environment is verified. In the first 10 years of the 21st century there was a frequent closing of rural schools. According to the School Census, between 2000 and 2009 more than 34 thousand establishments responsible for teaching in rural areas were closed. Of these, about 90% were municipal. There are several reasons for this: the reduction of the birth rate, the decrease of the rural population over the years among other factors.

Meanwhile, the Brazilian federal government, through the National Education Development Fund, distributes on its website building projects to be implemented in settlements or small rural communities in the various regions of Brazil. On the website of

the National Fund for Education Development various types of school projects are available to be downloaded by municipalities or any other person.

It is assumed that the standard design (Government project) has high energy expenditure embedded in its materials and is not suitable for a fluctuating demand. Thus, the use of a temporary architectural system can meet the needs of various natures demanded by buildings characteristic of public educational institutions. As a case study, the Rural Educational Space Project of 2 Classrooms was chosen and as a goal of Design Science Research a timber construction, as a temporary alternative, was developed. The temporary module reached  $238.3 \text{ m}^2$  based on the same program of the FNDE school, which has  $208.53 \text{ m}^2$ . The area difference of only 14% is due to the difference in size of the bathrooms and the covered patio.

### **Construction systems of temporary architecture**

Transportable and temporary construction systems can be divided into three specific types according to Kronenburg (2013): portable buildings are those that can be transported whole and intact and are usually manufactured and then transported to the site of deployment; relocatable buildings are transported in parts and mounted on the spot almost instantaneously; and demountable buildings are those that are transported in a number of pieces for assembly in the location stipulated by the project. They are much more flexible in size and layout and can usually be transported within a relatively compact space.

These characteristics can usually be found in temporary structures designed to respond to post-disaster emergencies. And because they are meeting an emergency demand, the rapid assembly of their structures must be guaranteed. This rapidity can be achieved through the pre-fabrication of its components that can be both part of a closed and open system.

In closed systems all elements are produced by a single manufacturer. In this context, the portable and relocatable buildings treated by Kronenburg (2013) could be included in this category. Closed systems can be developed for either whole buildings or as part of systems. All elements are coordinated and harmonized with each other and cannot simply be changed or extended as desired. Elements of a closed system can only be used within a particular system (Staib, 2008). For temporary constructions using prefabricated components, the use of "closed prefabricated systems" for the provision of emergency shelters, for example, is commonly criticized negatively. The term "closed prefabricated systems" is the process of industrialization of constructions having rigid and non-modifiable configurations in their shapes, and transportable to their places of implantation. A major disadvantage of such systems is their inflexibility to meet the varied needs of users (Abulnour, 2014).

Open systems offer the opportunity to use products from different manufacturers. Compared to the closed system, the combination of several prefabricated building elements is used to compose the building. The demountable building could fit in this system, for example. When designing with the open system, the designer determines the function of each component and selects potential manufacturers for such elements. In order to minimize the difficulties of assembly, the elements are, first and foremost, standardized, coordinating the sizing and decisions about the assembly rules and variations are elaborated. There should be the possibility of adding, changing and varying the types of standardized elements in order to allow variations according to the changes of function of the buildings (Staib, 2008).

## Temporary Educational Module

The wooden building was developed from the beginning with the purpose of being adaptable and demountable, besides wanting to provide the facility of construction to the future users. Based on these premises, the project was developed using as few different pre-fabricated elements and constructive components as possible. These elements are: linear elements of eucalyptus of 10 cm of square section and of 1.5 m of length; Steel connector (10 cm x 10 cm x 10 cm); steel cables to form the flat truss; 2 types of wood panels (0.5 m x 3.1 m and 0.6 m x 3.1 m) for floors and fences and first cover (lining); And roofing panels of waterproofed wood.

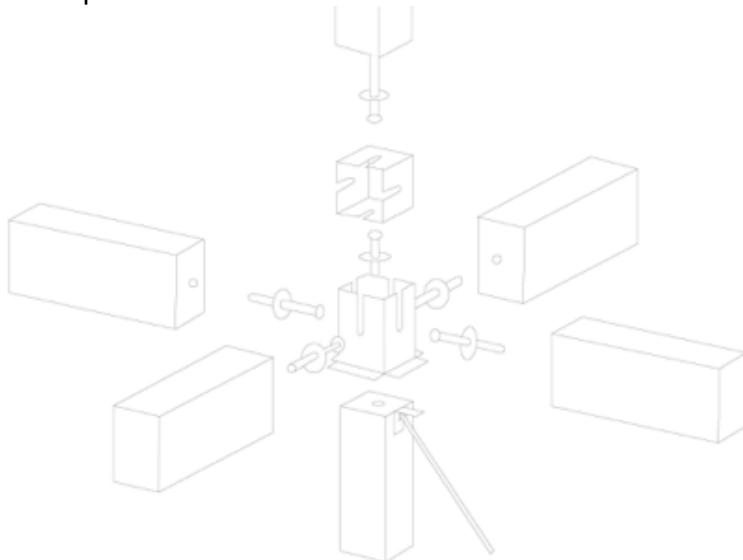


Figure 1. Preliminary study of connector detail

For the development of the building, plan (programmatic organization, accesses), sections and structures were thought concomitantly and in modules. In order to structure the school, it was thought to compose structural frameworks through the association between linear elements, similar to the one designed by Shigeru Ban (Steven and Lawrence, 2012), but using connectors and cables of steel as shown in the following figure:

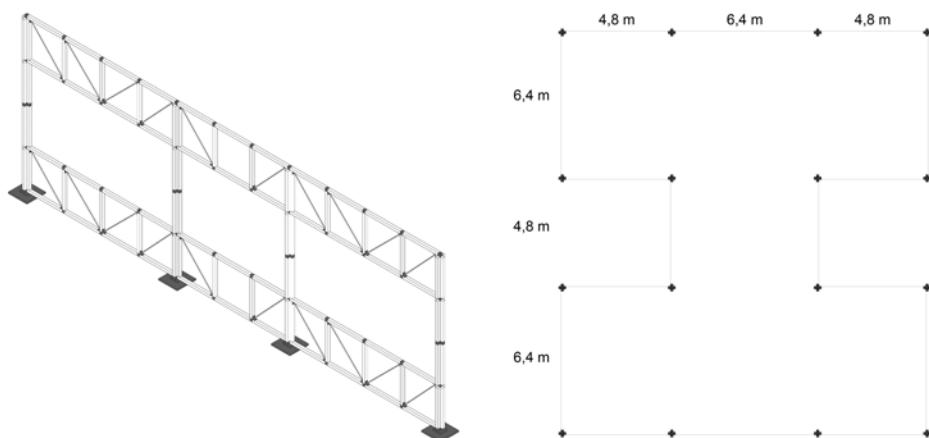


Figure 2. Preliminary study of the structural framework formed by linear elements

Through the structural frame and its repetitions (4 times) as can be seen in Figure 2, the school macrostructure was established. After this step, it was necessary to lock the

frames together using the same elements used to conform the macrostructure. These construction components were designed to be coupled by fittings and / or screws, which would support future spatial changes such as growth on one axis and another, as well as their disassembly. After assembling the school structures, wooden panels (floor and partitions) would be positioned to spatially organize the school. These steps can be checked by the following image:

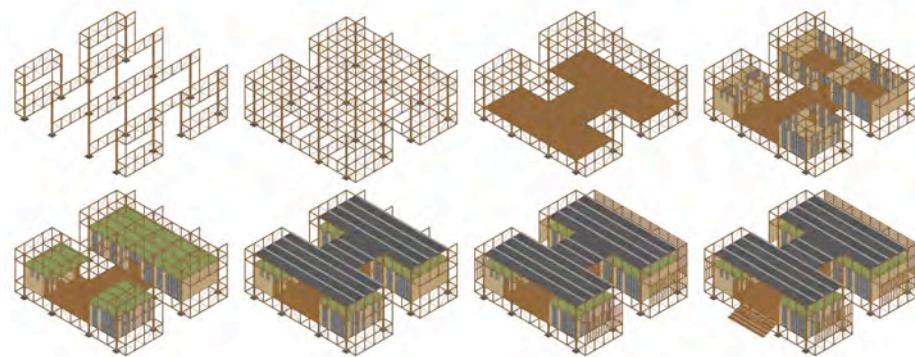


Figure 3. Constructive scheme of temporary educational wooden module

The school was divided into 3 parts: didactic sector, administrative sector and public sector. Last one, besides containing the bathrooms, articulates the other sectors as well as distributes the flows of the educational module, concentrating them in the south portion of the building with a certain type of control according to the following figure:

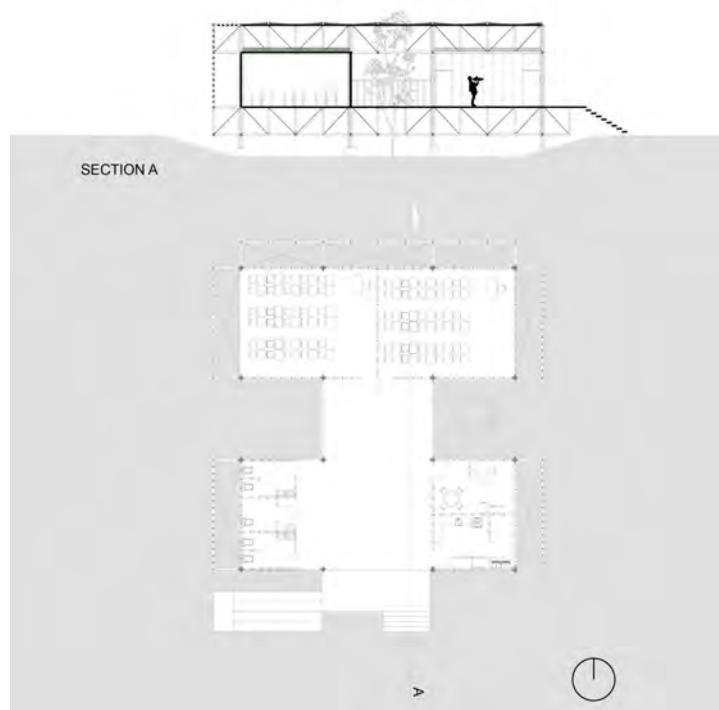


Figure 4. Section and plan of temporary wooden building

## The Rural Educational Space Project of 2 Classrooms

According to the design documents, it was made to be set up in settlements or small rural communities in various regions of Brazil. The school was designed in coated brick masonry and the structure in reinforced concrete. The roof consists of ceramic tiles on a wooden framework. The plan comprises a single room, administration, kitchen and toilets. The floor consists of abrasion resistant ceramics. Likewise, classrooms and facade are lined with a ceramic barrier, protecting the wall from moisture and impacts.

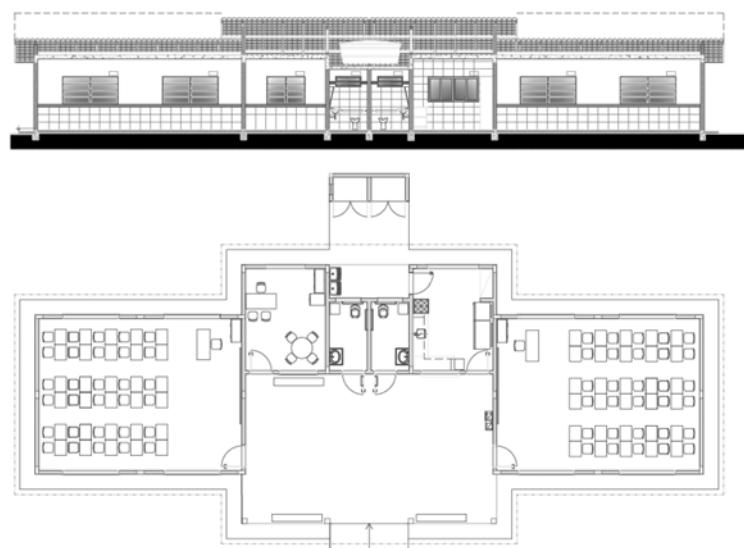


Figure 5. Section and plan of permanent building

## Energy lifecycle of the buildings

According to Tavares (2006), an Energy Life Cycle Analysis is a simplified but significant way to prepare an environmental impact analysis. It is based on the Life Cycle Analysis of the ISO 14040 standard and prioritizes the inventory of energy consumption data, direct and indirect. Although it does not use the concept of multiple analyses, characteristic of the Life Cycle Analysis, a Building Life Cycle Analysis allows the evaluation of relevant environmental impacts. In addition, because it has a simpler structure, it demands less costs and time. The purpose of a Building Life Cycle Analysis is not to replace a broad environmental analysis method such as a Life Cycle Analysis, but to support decisionmaking about energy efficiency and impacts (Fay, 2000).

First, on the basis of the FNDE budget worksheet containing quantitative data of the school design, as well as using works by Tavares (2006) and Monich (2012), among others, the Initial Embodied Energy was computed for both the Rural Educational Space Project of 02 classrooms and the Temporary module (Figure 6).

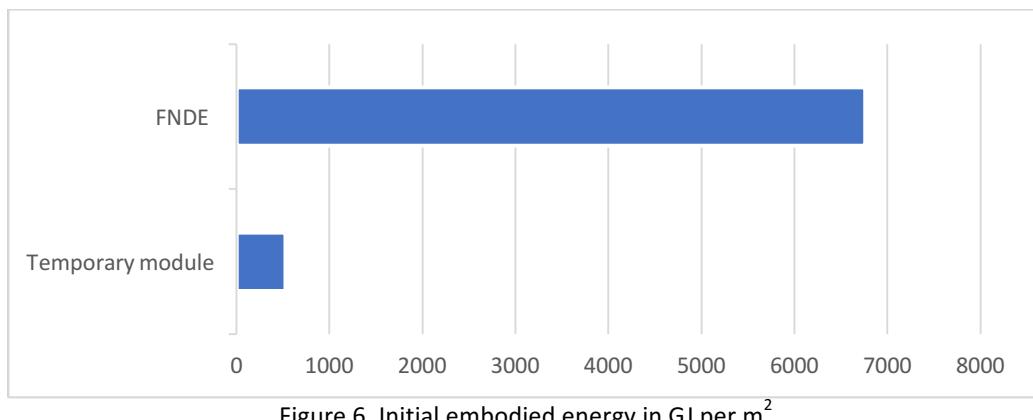


Figure 6. Initial embodied energy in GJ per m<sup>2</sup>

The temporary module obtained 524.30 GJ while the FNDE obtained 6763.31 GJ. It is a very significant difference since the value of the FNDE corresponds to approximately 13 times the value of that one. If we divide the respective values by the areas, we obtain the value of 2.20 GJ / m<sup>2</sup> for the temporary module and 32.43 GJ / m<sup>2</sup> for the FNDE. The difference in values per m<sup>2</sup> is 14.74 times.

Simulations were made to obtain the Operation Energy of the projects. In order for the simulation to be carried out, some items were then defined: architectural designs, the basic 3D model - model with only the faces of the planes using the SketchUp tool, deployment orientation, representation of the types of walls and roofs and the specifications of the materials. These specifications were provided at the level of details, such as thermal conductivity values, specific mass, specific heat, solar radiation absorption of all layers of walls, floors and ceiling. All data were then fed into the Energy Plus software, version 8.3, to calculate the energy consumption at the operation. Further input data included the range of thermal comfort, ventilation air flow, and lighting power. The simulated period was established between January 1 and December 31. The thermal comfort range was established between 18.5°C and 26°C; Ventilation was defined as 5 ac / h between 07:00 and 23:00; lighting power density was of 20 W / m<sup>2</sup>. Results comprised Site outdoor air drybulb temperature; (monthly); Zone air temperature; (monthly); Zone Ideal Loads Zone Total Cooling Energy; (monthly); and Zone Ideal Loads Zone Total Heating Energy (monthly).

Table 1. Operation energy of designs (F: FNDE / T: Temporary)

	Heating	COP	Cooling	COP	Total Year (kWh)	Sum (year)	kWh / m <sup>2</sup>	GJ / m <sup>2</sup>
F. Classroom1	36.55	5	5295.77	3	1772.57	4058.31	19.46	0.07
F. Classroom2	31.87	5	6151.9	3	2057.01			
F. Administration	56.38	5	652.39	3	228.74			
T. Classroom 1	53.84	5	9692.75	3	3241.68	7971.25	33.45	0.12
T. Classroom 2	49.84	5	10585.49	3	3538.46			
T. Administration	64.64	5	3534.53	3	1191.10			

In terms of operation energy, the temporary module could not prove to be best. The use of vegetal coverings to increase the thermal inertia was an important factor so that the difference between the values was not even greater. The FNDE project obtained 0.07 GJ /

$\text{m}^2$  (14.60 GJ) while the temporary one obtained 0.12 GJ /  $\text{m}^2$  (28.70 GJ). This means that the proposed module has an operation energy 1.7 times bigger than that of FNDE.

New buildings that benefit from recycled or reuse materials may draw from their embedded energies the values of the materials used (Adalberth, 1997; Fay, 1999; Scheuer, 2003). Within this idea, the residual energy can be verified. It consists of the difference between the initial embodied energy of a material and the multiplication of that energy with the replacement factor of that material. This replacement factor is obtained by dividing the estimated life cycle of the material by its technical lifetime, in years. As for the residual energy, the difference between the projects proves once again significant. It is the energy that would theoretically be conserved in building materials for reuse. The difference here is that while the temporary module can make good use of this energy after the functional life stipulated in the research, the FNDE project can not precisely be conceived as a demountable temporary building. That is, this energy (from FNDE building) would be, if not well recycled or reused, totally lost. The temporary module obtained the value of 383.68 GJ while the FNDE obtained the value of 4748.90 GJ.

Along 10 years, the difference in operation energy between temporary and FNDE yields 140.9 GJ. However, the residual energy of the temporary module allows to amortize that difference in operation energy. As a conclusion, the temporary timber design stands out in the global scope as the most environmentally sustainable project in all stages.

Table 2. Residual energy of projects

	Operation (GJ)	Time (years)	Operation x Time	Energy difference between designs (GJ)	Residual energy (GJ)	Resulting residual (GJ)
Temporary	28,70	10	287	140,9	383,68	242,82
FNDE	14,61	10	146,1	0	- 4748,9	- 4748,90

## Conclusions

Noticeably, the temporary educational module design stood out in relation to the FNDE design as the most environmentally sustainable choice. Such result is due to the combination of a reasonable operating performance with very low initial energy and residual energy, besides ensuring a good adaptability and disassembly of the building (thus conserving the embodied energy). Last two features were achieved thanks to a planning during the design phase that aimed at the minimization of constructive elements, so that from the union of these, through the dry connections, the building could be erected. This building could be constructed to meet the floating demands of the fields and suburbs, and after resolving them, be disassembled to meet other demands elsewhere or be stocked up to a second order.

## References

- Abulnour, A. H. (2014). The post-disaster temporary dwelling: Fundamentals of provision, design and construction. *HBRC Journal*, 1 (10), pp. 10-24.
- Adalberth, K. (1997). Energy use during the life cycle of buildings: a method. *Building and Environment. Elsevier Science Ltd*, 32 (4), pp. 317-320.
- Fay, R.; Treolar, G.; Iyer-raniga, U. (2000). Life-cycle energy analysis of buildings: a case study. *Building Research and Information*, 28 (1), pp. 31-41.
- Instituto Brasileiro de Geografia e Estatística (IBGE). Pesquisa Nacional por Amostra de Domicílios (Pnad): séries históricas e estatísticas. Available in: <<http://seriesestatisticas.ibge.gov.br/series.aspx?vcodigo=PD171>>.
- Kronenburg, Robert. (2013). *Architecture in Motion: The history and development of portable building*. Routledge, Oxford.
- Monich, C. R. (2012). *Environmental evaluation of a pre-fabricated social housing in the Wood Frame system in the State of Paraná*. Master. Federal University of Parana.
- Scheuer, Chris et al. (2003). Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. *Energy and Buildings*, 35, pp. 1049-1064.
- Staib, Gerald. (2008). *Components and systems: modular construction: design, structure, new technologies*. Munchen.
- Steven J. P., Lawrence C. B. (2012). Portals to an architecture: design of a temporary structure with paper tube arches. *Construction and Building Materials*, 30, pp. 657-666.
- Tavares, S. F. (2006). *Methodology of analysis of the energetic life cycle of brazilian residential buildings*. Doctorate. Federal University of Santa Catarina.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## How to provide “Better” rammed-earth buildings to villagers after earthquake in Southwest China - A case study of Ludian Reconstruction project

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**Abstract:** Rural construction is an important issue in the contemporary development of China given that a growing number of buildings that have been built do not follow traditional culture and the local environment. Significant challenges exist in implementing permanent housing reconstruction programs after the occurrence of earthquakes because of the lack of systematic and effective guidelines in poor the safety of their traditional rammed-earth buildings. However, the price of building materials rapidly increased and exceeded the acceptable budget limit for most local villagers. Our research team decided to use “local technology, local materials, and local labor” (3L) strategies in the reconstruction project. We improved the traditional rammed-earth technology by using “high science and low technology” theory, which mainly focuses on seismic capacity, thermal comfort, and cost of construction. We built two demonstration projects which made rational use of local materials and technology to rebuild the rural communities, while respecting traditional culture and the autonomy of villagers. The concept of “collaborative construction” not only provided an opportunity for local labor force to learn new skills, but also reduced economic pressure on house construction. The projects will also provide a reference for the local government to formulate rules for reconstruction projects.

**Keywords:** Better rammed-earth building, after earthquake

### Introduction

Ludian County is located between 568 and 3356 m above sea level in Zhaotong Prefecture, Northeast Yunnan. The county has a total area of 1,519 square kilometers, of which 87.9% is characterized by mountains and valleys. This terrain makes transportation inconvenient and impedes the development of the area. Ludian has a low latitude upland monsoon climate. No significant temperature difference exists among the four seasons. Annual average temperature is 12.1 °C, and annual average rainfall is 923.5 mm. The 2014 Ludian earthquake with a moment magnitude of 6.1 struck Ludian County with a focal depth of 12 km on August 3, 2014. The earthquake claimed 617 lives. A total of 112 people were reported missing, and several people were injured. Over 80,900 houses collapsed and 129,100 were severely damaged (BBC 2014). After the earthquake, the challenges of reconstruction work include:

- bad anti-seismic performance of traditional rammed-earth buildings
- significant increase in the price of construction materials
- how to deal with the construction waste of damaged buildings in earthquake
- poor thermal performance of brick-concrete buildings
- lack of local labor

The villagers lost confidence in the performance of traditional rammed-earth buildings. They are now eager to build houses that are anti-seismic, cheap, and comfortable. The

following SWOT analysis (Table 1) shows that rammed-earth buildings have a number of advantages in meeting the needs of poor rural areas of Southwest China. Improving the anti-seismic performance and durability of rammed-earth buildings has become a highly important issue for earthquake-prone areas. Mitigation of seismic risk will therefore be possible only when the villagers themselves adopt improved rammed-earth construction systems as an essential part of their own culture.

Table 1. SWOT analysis of rammed-earth building in Southwest China

	Helpful to achieving the objective	Harmful to achieving the objective
Internal attributes of the organization	<b>Strengths</b>	<b>Weaknesses</b>
	1.local materials 2.good thermal performance 3. regulate indoor humidity 4.low energy consumption and carbon emissions 5.little pollution 6.noise reduction 7.easy to learn 8.low construction cost 9.collaborative construction	1.bad anti-seismic performance 2.poor durability (waterproof/mothproof/moisture proof performance) 3.Non-standard materials 4.Labor-intensive construction
External attributes of the environment	<b>Opportunities</b>	<b>Threats</b>
	1.new countryside construction 2.the rise of ecological sustainability theory	1.misunderstanding of rammed-earth building- for village and officer 2.how to improve the anti-seismic performance

In collaboration with Professor Emily So of Cambridge University and Professor Bai of the Kunming University of Science and Technology, our team launched a Village Rebuilding Assistance Program in Guangming Village on October 2014. We aim to use “local technology, local materials, and local labor” (3L) strategies to design an anti-seismic building with traditional features at low cost but in an enhanced and comfortable living environment. In addition, we also hope to provide a basis for the local government to formulate reconstruction strategies.

### The progress of the reconstruction project

#### *First Demonstration Building*

Before the initiation of the design work, the team conducted a series of survey and investigation in the village to identify an appropriate solution. We then chose a family for the first demonstration building in Guangming village. The owner is a woman with two children and their living condition was poor. We designed a main house with rammed-earth and a kitchen with adobe brick (Figure 1-2). The project started in November 2014 and was completed in February 2015.

Before construction, the villagers were required to spend half a month to sieve and moisten the soil of the damaged building. The foundation of the main house and kitchen was a C15 rubble concrete structure with cement: sand: stone: water proportion of 50:124:221:33. After five to seven days of maintaining the foundation, villagers started to construct the main house. The φ8 steel bars are embedded every 1200mm in the wall especially in the corner

and both sides of the window which are weak in the structure. Steel bars inside the wall became an important part of an effective anti-seismic design because the bars connect the foundation and enhance the integrity of the houses. We changed the components of the wall (soil: sand: cement: grass: fibre proportion of 100:100:7:0.2:0.2) to increase the stability of the walls (Norton 1997). The use of local materials solved the construction waste problems of damaged buildings after earthquakes. Some concrete belts were added into the wall to improve structural integrity and avoid vertical cracking. To promote efficiency in this project, we used electrical rammed tools that were improved according to local manual technology. Several kinds of rammed heads were provided to fit the different parts of the wall. After the rammed-earth work, villagers spent four days building the C20 cast-in-place concrete floor and one month for the second floor and roof construction (Figure 3-10).

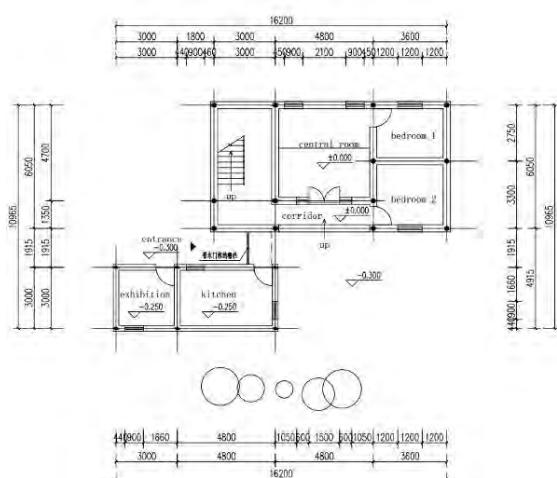


Figure 1. First floor plan

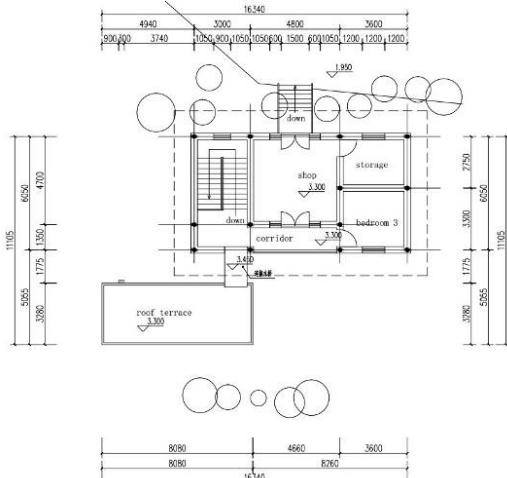


Figure 2. Second floor plan



Figure 3- 10. Main structure construction

### *Shaking Table Test*

To verify the improved technology we used in the reconstruction project, a shaking table test on a single-layered rammed-earth house pilot project was conducted in Kunming University of Science and Technology (Figure 11). The EL-Centro and Ludian earthquakes were used to simulate the conditions in the test. The sequence of the shaking table test included two selected earthquake acceleration records with peak values of 0.1, 0.22, 0.4, and 0.62 g. After the test, only several small cracks could be observed on the rammed-earth wall (Figure 12) (YNEERI 2015). Result shows that the seismic performance of the rammed-earth building significantly improved and can meet local seismic codes.



Figure 11. Rammed-earth model

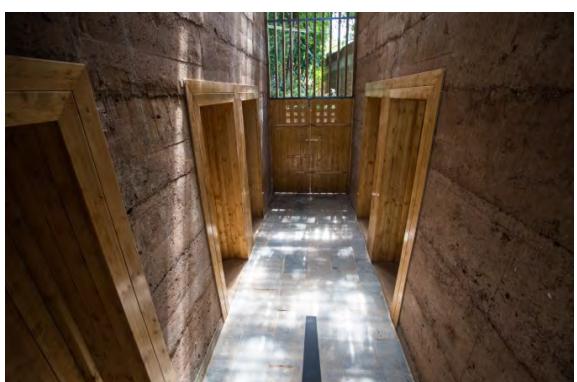


Figure 12. The state of model after test

### **Second Demonstration Building**

After a summary of the first building, the second demonstration building was built for an aged couple who lived in a tent after the earthquake. The second demonstration building was aimed to validate the systematic construction process and high building performance of the innovative rammed-earth building system. Within the limited land, the design was integrated with living and semi-outdoor spaces to provide a comfortable and artistic living environment for the aged couple. Double-glazed windows and insulated roof are used to improve the thermal performance of the building.

To improve seismic performance, the components of the wall were improved using a soil, sand, cement, grass and fibre proportions of 100:100:5:0.2:0.2 to ensure the stability of the wall. The concrete belts were hidden in the wall so that the earth facade could be integrated. The quality of the building materials, rammed tools and formwork was improved. The project started in December 2015 and was completed on April 2016 (Figure 13-19).



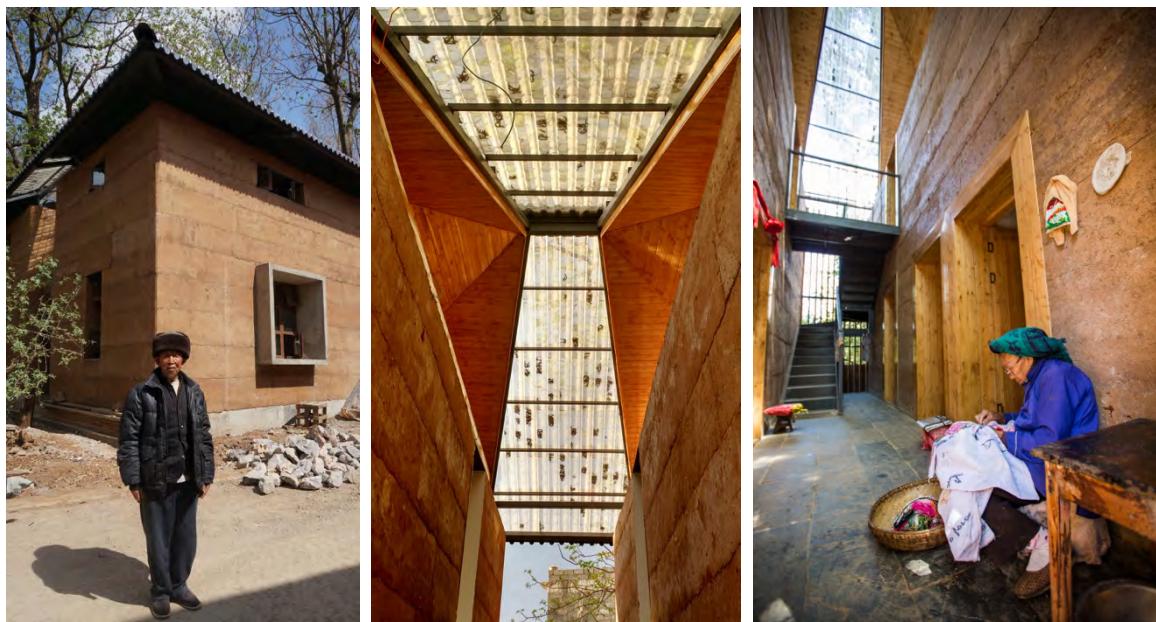


Figure 13-19. Second demonstration rammed-earth building

## Performance Evaluation

### *Cost Analysis*

We chose a brick-concrete building with the same area near our second demonstration building in Guangming village to compare the cost of second demonstration building in terms of three aspects: total, material, and labor costs. The details are shown as follows (Figure 20):

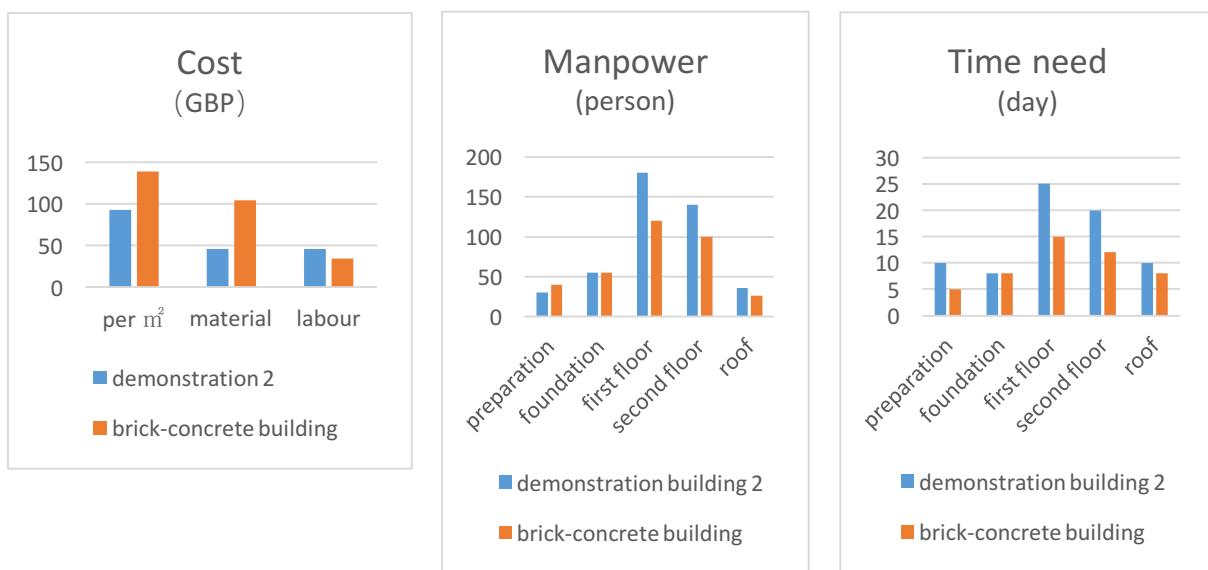


Figure 20-22. Cost, Manpower and Time need analysis

The chart shows that the average cost per square meter of the rammed-earth building is 33% lower than that of the brick-concrete building. This finding indicates the cost advantage of the rammed-earth building. However, the material cost of the rammed-earth building is only 44% of that of the brick-concrete building and the labor cost is 1.3 times. Thus, cost can still be reduced by optimizing manpower during construction. In future projects, we should improve technology in terms of two aspects:

- 1). Reduce manpower cost by improving the technology to enhance construction efficiency, as well as by encouraging collaborative construction among villagers.
- 2). Reduce the material cost. The proportion of cement and steel bars can be further reduced based on the results of the shaking table test.

### ***Manpower and Time-need Analysis***

The brick-concrete building with the same area was compared with the second demonstration rammed-earth building in terms of manpower and time needed to finish. The Figure 21 and 22 demonstrate that the foundation of the two buildings is almost the same. However, a significant difference was observed in terms of manpower and time needed between the first and second floor construction, which is also reflected in the project cost. The sloped roof of the rammed-earth building is more complicated than the flat roof of the brick-concrete building in terms of structure and construction technology. Thus, more manpower and time were needed to finish the former compared to those of the latter. In terms of construction preparation, sieving and ensuring the moisture of the soil in rammed-earth buildings required more time but did not need considerable manpower. Preparing and transporting the brick and steel bar in the brick-concrete buildings require significant effort but need a short amount of time. Thus, manpower and time needed to finish the brick-concrete buildings can be reduced by optimizing the design and the choice of rammed tools during construction (Taylor and Luther 2014).

### ***Thermal Performance Analysis***

Compared with conventional building materials in rural areas, earth materials have outstanding heat storage performance that can provide cooling effect to keep houses cool in summer and warmth in winter. Earth materials can effectively regulate indoor humidity and air quality. The figure 23 shows that the temperature of rammed-earth buildings is warmer than that of brick-concrete buildings in winter and cooler in summer. In comparison, the temperature fluctuation of rammed-earth building is lesser than that of the outdoor temperature of brick-concrete buildings. The figure also shows that the anti-seismic rammed-earth building has outstanding heat storage performance. The temperature of rammed-earth buildings remained low during winter because of the climate in Ludian. Thus, future projects should improve the self-insulation performance of rammed-earth buildings.

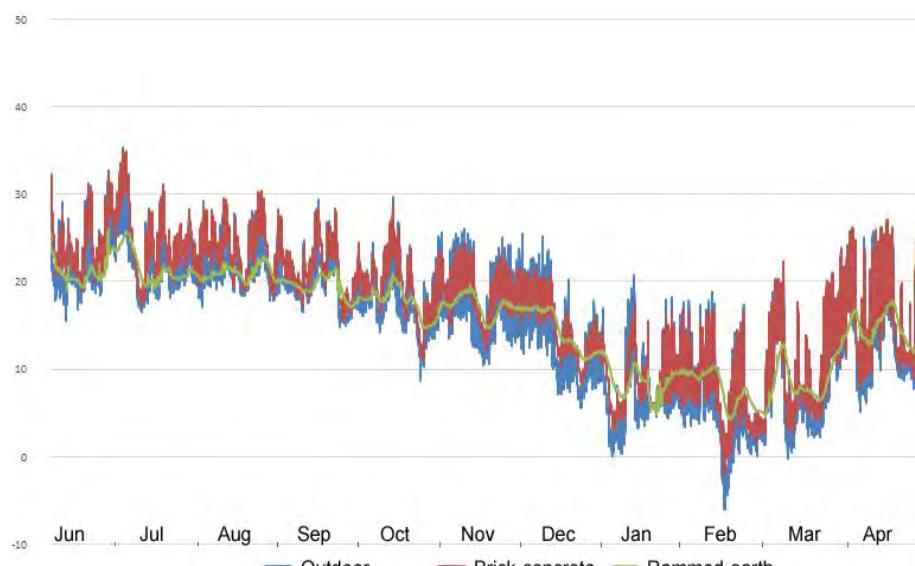
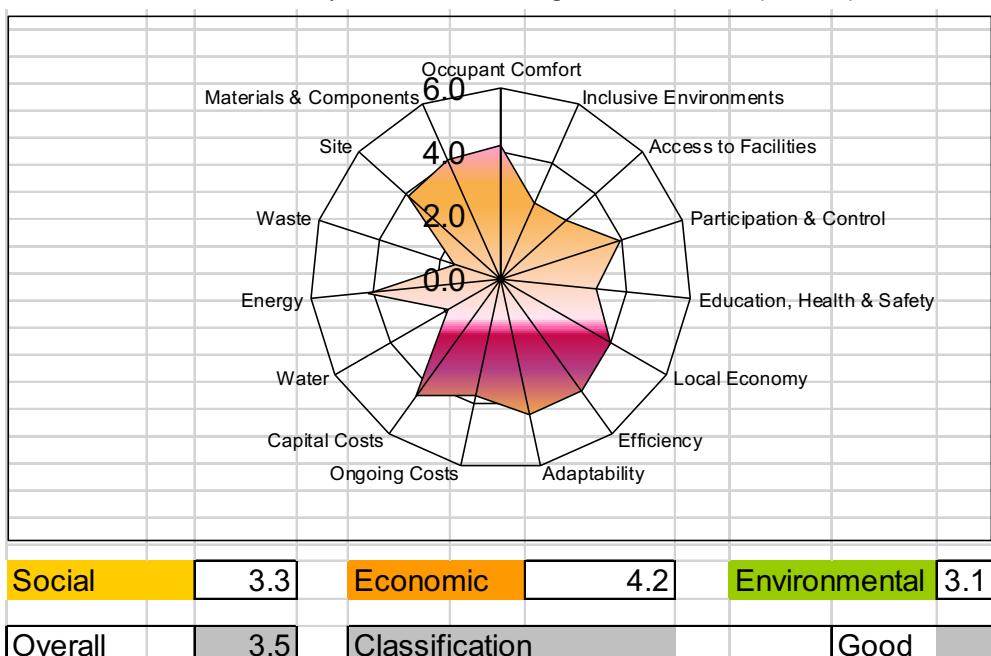


Figure 23. Thermal Performance analysis

### **Evaluated by Sustainable Building Assessment Tool (SBAT- P) V1**

Results show that the demonstration building is classified as Good in the SBAT system (Gibberd 2005). The economic dimension with a 4.2 grade shows that local materials and labor have a number of advantages for poor rural areas. With the participation and control of villagers, they will pay more money for ongoing costs, however, access to facilities and waste and water-recycling, will increase the amount of work done and improve sustained performance. For example, facilities for certain wastes, such as batteries, ink cartridges, fluorescent lamps should be established in the community. Gray water from washing/relatively clean processes also should be recycled and reused.

Table 2. Evaluated by Sustainable Building Assessment Tool (SBAT- P) V1



### **Project outcome and future work**

The 3L strategy has been used in our reconstruction project. The outcome could be summarized in three aspects. In the environmental dimension, the embodied energy and environmental impact of the houses are minimized. Good thermal and daylight performance guarantee low operating energy consumption.

In the economic dimension, construction and operating costs have been minimized to make it affordable to local residents. The villagers themselves constructed the houses mainly with simple tools. Once skills were transferred, the villagers can easily improve and maintain the houses in the future. They can also utilize this technology as a means of earning their livelihood (WAN 2012).

In the social dimension, local residents were fully engaged in the entire process of reconstruction. Multidisciplinary university resources were fully used to support rural reconstruction. The local government is also involved in learning and practicing this new sustainable method of rural reconstruction. Rammed-earth construction has a long history in China. We protected this kind of construction method and lifestyle by improving its building performance with local materials and a simple strategy.

In subsequent stages, this anti-seismic earth building system will be applied to more rural community reconstruction projects in Yunnan Province, China. The investigation and

design of two village reconstruction projects are currently in progress. After a series of practice and research, books and guidelines will be published to systematically document this method and provide a reference for national reconstruction policies and seismic standards for buildings made of earth materials in the future.

### **Conclusion**

The Ludian case study shows that local materials and technology can be used in reconstruction projects, especially in poor rural areas. The project fully respects the traditional culture and autonomy of the local villagers, both of which constitute the core of local community development. The concept of “collaborative construction” not only provided an opportunity for the local labor force to learn new skills, but also reduced the economic pressure on house construction (Chi and Ng 2014).

The 3L strategy emphasizes on the concept of sustainability and focuses on the importance of the locals in poor rural areas. The strategy suggests a self-sufficient, regional character-based model that is suitable for reconstruction in poor rural areas, which have poor transportation and a backward economy. It can also reduce the communities’ dependence on external assistance by emphasizing the use of local resource and traditional core values. The 3L strategy can provide a systemic way to further study sustainable reconstruction and community renewal in poor rural areas.

### **References**

- BBC. (2014). China earthquake: Troops join race to aid survivors. Retrieved from <http://www.bbc.com/news/world-asia-china-28635027>
- Chi, X., & Ng, E. (2014). Study on the Sustainable Renewal of Poor Rural Communities of Southwest China.
- Gibberd, J. (2005). *Assessing sustainable buildings in developing countries—the sustainable building assessment tool (SBAT) and the sustainable building lifecycle (SBL)*. Paper presented at the Proceedings of the world sustainable building conference. Tokyo.
- Norton, J. (1997). Building with earth. *Building with earth.; Building with earth: a handbook*.
- Taylor, P., & Luther, M. (2004). Evaluating rammed earth walls: a case study. *Solar Energy*, 76(1), 79-84.
- WAN, L. (2012). *Study of Built Environmental Sustainability Assessment of Poor Rural Areas of Southwest China*. The Chinese University of Hong Kong, Hong Kong.
- YNEERI. (2015). *Report of shaking table test: New rammed-earth building*. Retrieved from Kunming University of Science and Technology.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## An additive approach to the building envelope using Welsh-grown timber

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**Abstract:** This paper is focused on the use of Welsh-grown timber in the building envelope, through a series of prototype projects exploring species, technology and tectonic form. The Welsh timber industry relies heavily on the importation of sawnwood, timber board products and innovative, engineered timber systems to meet an increasing demand to improve construction efficiency and the environmental performance of the building envelope. Compared to Northern and Central Europe and regions such as the State of Vorarlberg in Austria, Wales is perceived as having an underdeveloped and underperforming timber construction industry with only 15% forest cover to supply a variety of timber sectors. Through an analysis of the properties of Welsh-grown soft and hardwoods and the technical and skill limitations and opportunities of the industry this paper will demonstrate that it is possible to use Welsh-grown timber for a variety of modular superstructure, cladding and external joinery systems. The conclusions identify limitations, including a lack of research and development investment, and a lack of knowledge and focused direction across the industry. However, the prototype projects show that the unique properties of timber, sustainably grown, managed and processed can be innovatively manufactured and assembled into prefabricated, additive components for the design and construction of the low-energy architectural building envelope.

**Keywords:** Wales, timber, construction, tectonics, prototypes

### Introduction

This paper is based on the hypothesis that it is possible to use Welsh-grown timber in the sustainable, architectural building envelope despite negative perceptions, poor timber properties, limited skills and access to technology within the Welsh and UK timber industry. A series of prototype projects, developed in collaboration with the construction and timber industries, are discussed that lead to an additive tectonic approach that is specific to Welsh-grown timber. Currently there remains a gap in the knowledge of and designing with, Welsh-grown timber.

Since 2000, the Design Research Unit Wales (DRUw) at the Welsh School of Architecture began working with Coed Cymru on a series of architectural projects exploiting the potential of Welsh-grown timber. The joint thesis was that if an architecture informed by ecological woodland practices could be encouraged and developed, it would contribute to a number of environmental, economic and social sustainable woodland, farm and river initiatives aimed at jointly having a positive impact on Welsh forestry and the built environment.

Welsh woodlands and forests are under resourced, under valued and in some opinions not managed for the future demands of both the ecology and economy (Jaakko Pöyry

Consulting, 2004). The timber and knowledge is available and there would appear to be a political, social and industry will to use local timber, as encouraged by the Welsh Government (Forestry Commission Wales, 2009). Furthermore, many timber businesses in Wales are willing to use homegrown timber and develop their product range and technology for new, innovative uses. This has been influenced by an increasing industry emphasis on sustainable, standardised, efficient construction methods. However, the small scale of the Welsh timber industry and an apparent lack of communication and structure between different parts of the supply chain have resulted in a lack of investment from both the public and private sector (Newman et al, 2015).

To date, the use of Welsh-grown timber in the external building envelope remains minimal compared to the volume of imported softwoods and timber products from Scandinavia and North America. Currently in Wales, there is a lack of innovative design precedent compared to regions such as the State of Vorarlberg in Austria where the technological and engineering enhancement contributes towards a low energy, timber architecture. (Bryans, 2011) As a result the social, cultural and ecological history of the locality, often contained within the ancient woodlands, can be reflected in the application and use of the timber in the architecture from the outset. This would reflect a return to the historical way of building, where an understanding of the local environmental, social and economic parameters that form society can be fully appreciated.

### **Welsh forest context**

There are approximately 306 000 hectares, comprised of an almost even split between broadleaf and coniferous woodland, covering 15% of the total land area of Wales (Forestry Commission, 2014). However this forest cover is considerably lower than other parts of Europe (45% average), Japan (69%), Canada (34%) and the United States of America (33%) that have developed forestry and adapted to changing demands (Food and Agriculture Organization, 2010). As a result the construction industry in Wales, relies heavily on the importation of both sawnwood and innovative timber products.

In contrast, current production of Welsh-grown timber is stable, meeting the demands of a number of established supply chains and market demands. However, the crop is considered by many in the industry to have limited commercial value and use, often seen as waste for processing as pulp and wood fibre for paper, wood-based panels, pallets and fuel (Forestry Commission, 2014).

Since 1989, Coed Cymru (2015a) have been working collaboratively alongside the Forestry Commission, woodland owners, contractors and timber users to heighten awareness of native woodlands, providing help, advice and training on the management of Welsh broadleaf woodland and simultaneously developing timber products and markets that ensures broadleaf woodlands have a firm economic base to ensure continued management. As a reaction against clear felling and the destruction of woodland biodiversity, selective felling is promoted as the most sustainable way of managing the forest. An example of this is the continuous cover forestry method (2015b), as an alternative '*silvicultural [system] whereby the forest canopy is maintained at one or more levels without clear felling*' (Mason et al, 1999). The approach is based on the principle that trees in the forest provide the framework for the wider forest ecosystem. In general this allows for small, dispersed felling sites within the forest relying on natural regeneration to repopulate, in order to ensure that the species most appropriate to that context will be cultivated. In this way the variation in site conditions within the forest provides a source of species diversity.

It is proposed that crooked young and medium growth trees (diameter +/-15cm) in the woodland are selected for felling. These trees, which previously were used as firewood, are proposed for use in construction. The remaining straight trees are left to keep growing, and not cut for the immediate supply of timber, thus developing a mature growth forest, and a supply of hi-grade, large section, quality timber for future generations. Predominantly employed on private woodlands, thinning, coppicing and pruning carried out over decades, produce small-scale timber quantities, prior to an eventual final felling. The techniques chosen can differ between individual foresters, but are often species and climate specific.

### **Prototype designs**

The diverse collaboration between DRUw and industry was based on forest practice, timber experiments, technical and biological innovation and design led creative practice with a focus on place, environment, identity and tectonic form. 10 live design projects emerged and incorporated ideas exploring different scales, spans, and functions in differing environments, contexts and landscapes. The process enabled an ongoing reflective conversation between projects, responding to scientific and technical research from industry and specialists that was tested in practice-based design research (Candy, 2006) through bottom-up construction of prototype components, assemblies and buildings and top-down client lead design. Often prototypes of glued, screwed or jointed beech, Sitka spruce or oak were developed as workshop experiments to improve stability, reduce wastage and improve structural performance utilising small sections and short lengths of timber. These prototypes have been characterised under the following headings in relation to the approach to using Welsh-grown timber.

#### **Standardised hardwoods**

An early prototype for a beach safety building at Port Eynon on the Gower Peninsula, provided the opportunity to use a number of products, trademarked as the 'Welsh Angle', using Welsh-grown hardwoods in an exposed location. Inspired by the 'working' fisherman's storage huts at Rye illustrated in *The Functional Tradition*, (Richards, 1958) the beach hut was designed to protect and shelter lifeguards in inclement weather and to provide first aid facilities, sited at the border of a white sandy bay and a necklace of sand dunes.

Using only timber extracted through CCF woodland management techniques the specified hardwoods are based on short length, small to medium diameter timber specifically chosen for different parts of the beach hut for their properties in relation to availability, strength and durability: oak, sweet chestnut and beech.

Furthermore, a conversion process was developed which minimises waste, producing 100mm x 100mm sections sizes up to 1200mm long, therefore forming a principle module and bay size of 1200mm. 3 modules formed the basis of a 3600 x 3600mm plan and a 2 module floor-floor height over 2-storeys gave a beach hut height of 4800mm. The 1200mm frame would be infilled with prefabricated panels using a range of other modular timber products - a high performance laminated oak framed window and a beech internal floor cassette.



Figures 1&2. Beach hut perspective and tectonic model exploring material and spatial proportion.

### **Engineered softwood**

With limited technology to laminate large-scale beams and panels in Wales, a collaborative stress-lam prototype was established between a forester, carpenter and engineer. The project targeted a number of technological, performance and design questions posed by the industry - how to design a modular, low-tech, solid construction solution to construct building components such as walls, floors and roofs. The stress-lam system is a dry construction process that requires little space, time, expertise or specialist machinery.

Stress-lam employs a low-tech construction process to generate friction, counteracting rotational movement, between small lengths of timber using bolts, cables or even rope, eliminating the use of glue and the need for post-press planning. In doing so, small sections and standard lengths of lower quality and un-graded Welsh-grown softwood (Norway and Sitka spruce, larch, Douglas fir and Western hemlock) can be utilised minimising the need for defect cutting and wastage. Similar systems have been used in the USA and Australia in bridge construction, while a more directly comparable form of construction process appears in the 'Carbon Café', in Helsinki by the Wood Studio.

The table prototype was fabricated in five structural panels using 18no. 50mm x 100mm timber lamella bolted together over a 900mm width at 600mm centres with M12 stainless steel threaded rod. Each timber was tongue and grooved to align each lamella, providing a smooth surface and resist torsional movement. In principle the panels can be made up from two standard lengths of timber, 1200mm and 2400mm, although other lengths, as appropriate can be incorporated for bespoke sizes or to accommodate non-standard timber.



Figures 2&3. Tectonic model of table; and axonometric exploring additive, small section, short length construction

### ***The integrated timber building envelope***

This three-year, UK Government<sup>1</sup> funded, project was to develop a low-cost, low-energy, affordable, rural housing system known as Ty Unnos - 'House in one night'. The primary aim was to design, fabricate and prototype a solution for the use of homegrown Sitka spruce in an elegant architectural solution determined by the following architectural and technological factors:

- Use standardised sizes of Sitka spruce and other softwoods available from the local sawmills;
- Use low-tech engineering methods complimenting available skills and plant to reduce costs and enable quick mobilisation;
- Focus on a domestic scale superstructure system that promotes high architectural design solutions and low carbon performance.

Influenced by architectural system precedents developed by Konrad Wachsmann, Walter Gropius, Walter Segal and Jørn Utzon, Ty Unnos was developed as a number of modules similar to Welsh cruck-framed houses and corresponding to the sizes of timber and the functions of a house: 1 Lobby & WC; 2 Bathroom, small bedroom & study; 3 Medium bedroom, kitchen & dining room; and 4 Living room & large bedroom. Spatial modules were then combined to form varying house types using the same components.

Fabricating 220mm x 280mm insulated box section post and beams to create 'portal' frames reduced the thermal bridging of solid timber structures, produced structurally stronger and more stable components from standard 50mm x 225mm, C16 Sitka spruce. The initial low-tech press and box section profiles were designed to allow for 15minutes of pressure, using steel sections, kitchen worktop and fire hose, before being left to cure.

Structural rigidity of the portal frames was provided through the jointing of the box section components using either: M12 or M16 studs resin bonded into the end grain of a box section; or 'L' shaped insert connectors from laminated hardwoods.

The principle for wall, floor and roof infill, embrace the same philosophy: Cassettes, boxes or panels using the 50mm x 225mm re-sawn to 25mm boards to create either insulated box sections, ladder trusses or SIPs. Window and door components were proposed to be standardised to compliment the module proportions using the 'Welsh Angle' principle.

Three prototype structures were built to test and explore potential of the system, leading to an ETAG approval for the manufacture of box section frames:

### ***Smithsonian Pavilion for the Smithsonian Folklife Festival, Washington DC, USA***

The proposal was for a two bedroom, single storey, house type inspired by the elemental components of vernacular Welsh rural domestic architecture, such as hearth and zonal separation between spaces. The structure was designed to test the structural, spatial and material performance of the components in a non-weathertight, un-insulated exhibition pavilion, fabricated in Wales and shipped to Washington DC for assembly.

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<sup>1</sup> The collaboration extended to the School of the Environment and Natural Resources, University of Wales, Bangor and Cowley Timberwork Ltd initially funded by the Countryside Council for Wales (CCW) and the Wales Forest Business Partnership. Further funding was awarded from Technology Strategy Board, Low Impact Building Systems in 2009 in collaboration with Burroughs, structural engineers.



Figures 7&8. Completed pavilion on the Mall, Washington DC; Exploded axonometric of modular Ty Unnos components

#### *Environmental Resource Centre, Ebbw Vale*

The 140sqm Environmental Resource Classroom is run by Gwent Wildlife Trust, to allow local school children and community to explore the heritage and ecology of the former steelworks site. It provided the first opportunity to utilise the Ty Unnos components in a fully functioning, weathertight building. The classroom was designed as a didactic study into simple, modular construction techniques expressing the local materials and how the building is constructed, heated and ventilated. Playful graphics, for children to explore, behind hit and miss charred Sitka spruce cladding responds to local wildlife habitats.



Figures 9&10. Ty Unnos components in construction; Interior of ERC with exposed construction language.

#### *Low energy Longhouse, Ebbw Vale.*

The 2 bed, 4 person affordable, low energy house, was won through an open design competition conducted by the Welsh Future Homes project utilising Welsh oak, green sweet chestnut, sycamore and Sitka spruce. The prototype was for a fully developed and regulatory compliant 2-storey Ty Unnos house designed and built to test the complete integrated system from a fabric-first approach to U-values, thermal bridging and air tightness. Materials, suppliers and manufacturers were limited to the local supply chain using standard and modular, readily available products that led to the development of a laminated chestnut, insulated framed, double sealed window component.



Figures 8&9. Axonometric of Ty Unnos components and environmental strategy; Longhouse south elevation.

## Additive design

On reflection, the collaborative prototyping and architectural design demonstrated that not only can Welsh-grown timber be innovatively fabricated and assembled into prefabricated, components for the design and construction of the low-energy architectural building envelope but the properties, technology and skills available have informed an additive tectonic approach that is specific to Wales.

The design and construction of a standardised, prefabricated timber architecture based on repeating species, components, elements and spaces draws inspiration from Jørn Utzon's notion of Additive Architecture: '*A consistent exploitation of industrially produced building elements is only achieved when these elements can be added to buildings without the components in any way needing to be cut or adapted*'. (Utzon, 1970)

The use of Welsh-grown timber is best based on standard lengths and section sizes either determined by the process of sustainable woodland management and extraction or processed by sawmills. In both cases, this leads to an efficient production of timber with minimal wastage. This is the base timber component from which all products and elements are manufactured. It would therefore be the intention to use these lengths and sections as supplied or in exact divisions or multiples of standard lengths to maintain material efficiency. This, in turn, influences the module sizes of elements, panels and volumes to be composed into spatial compositions determined by context, climate and the client. The result is a tectonic expression unique to Welsh-grown timber but flexible to allow for expression and a contextual response.

Five aspects of an additive principle have been identified that incorporate the key findings from the prototype studies and highlight a way of working with Welsh-grown timber that is intended to be an approach to understanding and designing timber architecture. Specific details and sizes are only provided as a guide in relation to the prototype projects for each stage, and not predetermined or the only sizes available. Source, species, sawmill, secondary processing and design decisions all influence sizes and products that may differ from project to project and as technological investment allow.

The following additive principles are listed from woodland to architecture, although this could also be seen as a circular process of influence and inspiration. The additive principle operates simultaneously as a process, technical detail, design tool and expression that does not follow a sequence of stages, but represents both a bottom-up approach to timber use and fabrication and a top-down expression of Welsh-grown timber in the building envelope. The two meet within the timber and construction industries generating a tectonic timber architecture.

### 1. The species

The following species have been identified for possible use: Sitka spruce (30%), larch (8%), Douglas fir (4%), oak (10%), sweet chestnut (<1%) and/ or ash (7%). Woodland management and the extraction of small-medium diameter roundwood of all species, for processing provides the limiting factor by which industry and designers must initially subtract from before adding value.

### 2. Sawnwood, veneer and waste

The reduction of roundwood into standardised sizes is determined by the needs of the construction industry and an efficient exploitation of roundwood forming basic components or modules to be repeated, layered, multiplied and re-constituted, using standard high-yield C16 strength grade, softwood species instead of importing C24.

### 3. The engineered component

Components are engineered from multiple short lengths and small sections to manufacture rational, planar and rectilinear products. This additive approach suggests the engineering of all timber species through stacking, aligning, layering, cross-layering, sandwiching, finger-jointing and orienting to enhance the performance of the basic sawnwood, veneers, chips, strands and sawdust.

#### 4. The building element

Sawnwood, engineered timber and timber products are manufactured, fabricated and constructed into a range of modular and/ or prefabricated building envelope elements.

#### 5. The tectonic module

The culmination of the additive stacking and layering of timber components and elements is informed by an applied design grid based on repetitive modules. Modules may be elemental, panelised, volumetric or a hybrid combination but are repeated to provide structure, enclosure, finishes and define space. The resultant tectonic is honest to the use of Welsh-grown timber to provide an efficient, low-energy building envelope. In a similar approach to Utzon's additive principle, space, composition, form and timber materiality are all expressed and respected as a tectonic timber architecture.

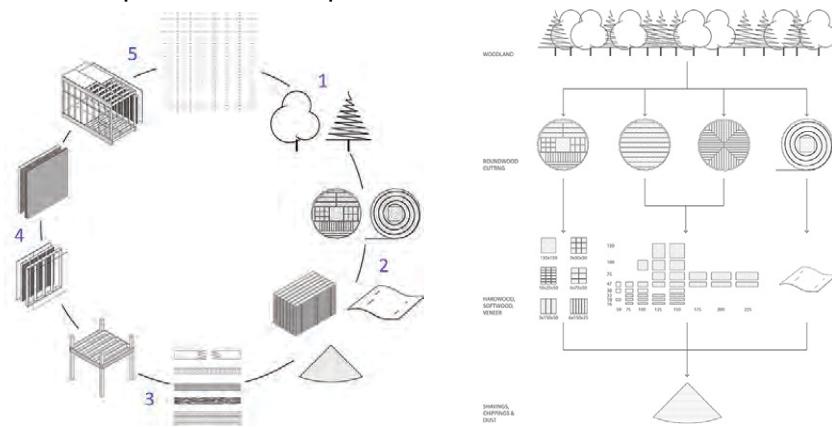


Figure 11. Stages of additive processing, manufacture and design

## References

- Jaakko Pöyry Consulting (2004). *Welsh Forest Industry: Mapping and Benchmarking the Forest Industry, Final Report (Executive Summary Only)*. London, Jaakko Pöyry Consulting
- Forestry Commission Wales (2009). *Woodlands for Wales: The Welsh Assembly Government's Strategy for Woodlands and Trees*. Cardiff, Welsh Assembly Government
- Newman, G; Hilton, G & Williams, G (2015). *Scoping a Roadmap for Delivering Sustainability and Growth of Welsh Woodlands*. Machynlleth, Wales Forest Business Partnership
- Stoney Bryans, T, (2011) *Integrated Strategies for the Welsh Timber Industry*. Cardiff, Low Carbon Research Institute
- Forestry Commission (2014), *Forestry Statistics 2014*. Edinburgh, Forestry Commission
- Food and Agriculture Organization of the United Nations (2010). *Global Forest Resources Assessment Main Report*. Rome, Food and Agriculture Organisation, p.224-228
- Coed Cymru (2015a). *Objectives and Targets*, Available from <http://www.coedcymru.org.uk/objectives.html> [accessed 17th August 2015]
- Coed Cymru (2015b), *Innovation*, Available from <http://www.coedcymru.org.uk/innovation.html> [Accessed 10th July 2015]
- Mason, B; Kerr, G & Simpson, J (1999). *What is Continuous Cover Forestry?* Edinburgh, Forestry Commission
- Candy, L (2006) 'Practice Based Research: A Guide', Creativity & Cognition Studios 1. Sydney, University of Technology
- Richards J.M, (1958) *The Functional Tradition in early industrial buildings; with photographs by Eric de Maré*. London, Architectural Press
- Utzon, J (1970). *Espansiva. Architektur*, 1(1970), 3-12



# PLEA 2017 EDINBURGH

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## **WORKING SPACE – an innovative modular timber construction system for the sustainable vertical extension of office buildings**

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**Abstract:** Urban densification issues are one of the key challenges for most European cities. In this context, the vertical extension of existing buildings provides a solution to create usable spaces without wasting additional land. Little attention has been given to office buildings, although, given their abundance in the building stock, they offer an important potential. The 'Working Space' project gathers an interdisciplinary research team around the development of an innovative, modular and prefabricated timber construction system. The dimensions of the latter can be adjusted to the structural grid of existing buildings and to a great variety of new typological organisations. The extension's envelope is based on the principles of bioclimatic architecture and combines active and passive elements. It features a high-performance insulation, provides a smart management of passive solar gains, natural ventilation and free cooling, and offers large surfaces dedicated to photovoltaic energy production and urban biodiversity. The system is composed of local materials with very low embodied energy. This paper presents the project's outcomes at different scales, ranging from urban design to construction details, and the outputs of an innovative life cycle assessment. A first application of the system, comprising 40 workspaces, is currently being conducted in Lausanne, Switzerland.

**Keywords:** sustainable architecture, modular construction, timber prefabrication, bioclimatic conception

### **Introduction**

#### ***A context of urban densification***

Several studies on sustainability issues have shown the many negative consequences of urban sprawl: waste of land, pressure on landscape, environmental impacts due to mobility, high infrastructural costs and worsening of socio-cultural inequalities (Rey, 2013). This has led to the development of new territorial strategies aiming to reverse the trend. Based on a better coordination between urbanization and mobility, the latter focus especially on an increase in population and employment density close to public transportation, on the valorisation of untapped potentials within constructed sites and on the promotion of high-density, mix-used urban polarities (Rey, 2011).

In this context, the vertical extension of existing buildings provides a solution to create usable spaces without wasting any additional land. A number of recent studies already have shown the potential of this approach in the field of residential buildings (Comtesse, 2008; Tulamo, 2014; HSLU/CCTP & al., 2016). Little attention has been given so far to office buildings, although, given their abundance in the building stock, they offer an important potential. In Switzerland for instance, residential buildings account for nearly half of the built-up areas, whereas tertiary buildings (including public, commercial and administrative

functions) represent around 20% of the total floor surfaces. These figures have remained relatively stable over the last 25 years (OFQC, 1991 & OFS, 2016). Furthermore, tertiary buildings usually present favourable conditions for vertical extensions in terms of construction typology (simple structural grids, large flat roofs, among others).

However, if an intensification of land use – in this case by vertical extension – is a necessary condition to reach more sustainability, it is certainly not sufficient (Williams, 2000). It indeed requires a global approach, including typological adaptability, energy efficiency and appropriate building materials. In addition, urban context specific constraints must be considered, such as difficult access to the construction site and the need for a rapid intervention to reduce disturbances on buildings already in operation.

The 'Working Space' project addresses these sustainability challenges at many levels. Gathering an interdisciplinary research team around a holistic integrated design process, it aims at developing an innovative, modular and prefabricated timber construction system taking all above-mentioned requirements and constraints into consideration. The present paper introduces the project's outcomes at different scales, ranging from urban design to construction details, and presents the outputs of an innovative life cycle assessment.

### **Integration of sustainability issues into the architectural concept**

#### ***Integrated design and prefabrication***

The construction system consists of a wooden structure, developed according to the principles of modularity and prefabrication. Its components are all adjustable to the different static systems and structural grids of existing buildings.

The vertical elements are made of a post-and-beam structure in laminated wood. This primary system allows to lean on a limited number of points and to easily transmit the loads on the existing structures. These large prefabricated elements also contain the main technical distributions. They can be placed either on the periphery or in the centre of the floor plan, thus giving maximum freedom for the design of interior spaces. The horizontal elements consist of wooden ribbed slabs, both for the flooring and for the ceiling. The dimensions of the latter exactly correspond to those of the vertical supports, and may vary in width from 1.80 to 3.60 metres.

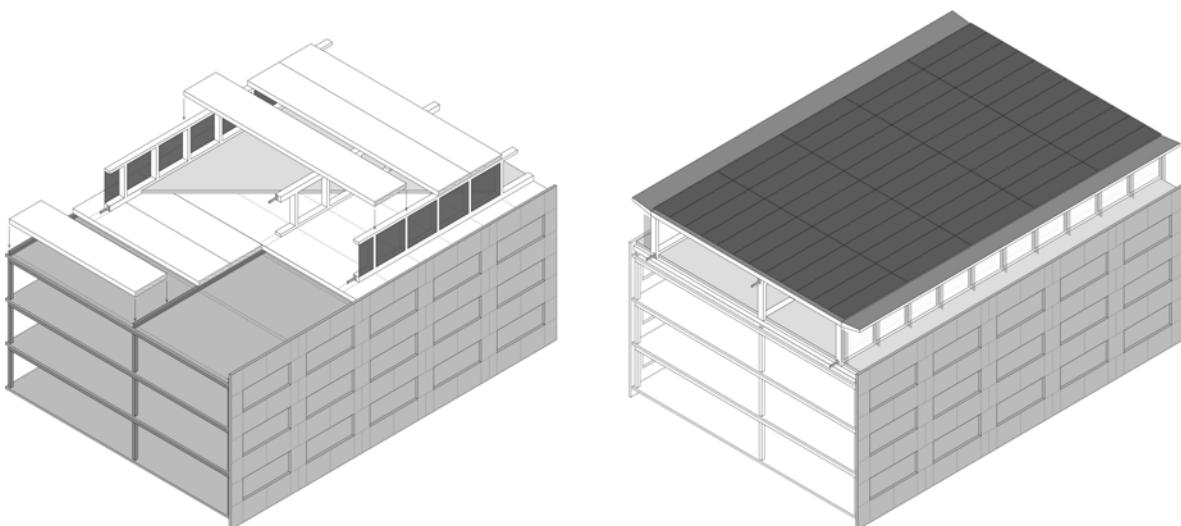


Figure 1. Axonometric views of the 'Working Space' construction system, based on a reference grid.

As shown in Figure 1, all façade components, like the fixed glazing, the openings, the mobile solar protections and the wind deflectors are designed in strict accordance with the same reference grid. This also applies to technical installations, notably the heating devices, the electrical wiring and the connections to the communication network. The result is a very high rate of prefabrication, as compared to common building standards. What is more, the optimised design of each construction component fosters the desired expression of lightness and simplicity, thus enhancing the global architectural quality.

### **Modularity and flexibility**

The modular principles of the 'Working Space' system enable great flexibility in the organisation of interior spaces, be it for administrative or educative purposes. The system's adaptive dimensions and its large glazed façades offer true liberty in almost any typological organisation.

In the administrative field, it is for instance possible to design large open spaces, meeting rooms or shared closed offices, or even individual cell offices (Figure 2). The system thus provides the necessary adaptability to meet future requirements, by addition or removal of non-load-bearing partitions.

Furthermore, with a ceiling height of 3.00 metres, the system also makes it possible to create training and educational spaces such as workshops or classrooms. Such a possibility opens interesting perspectives for the extension of existing school buildings.

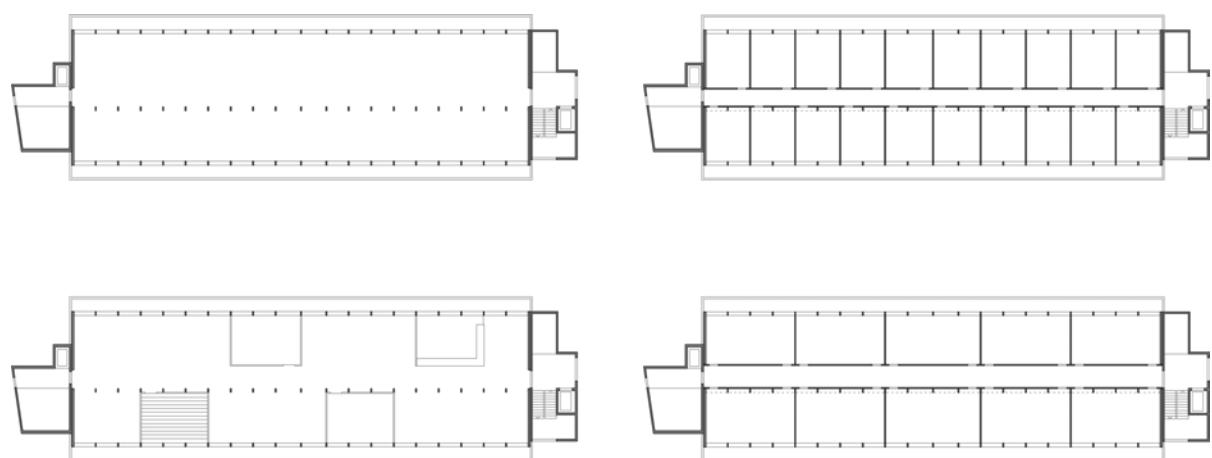


Figure 2. Different possible organisations of the ground plan with the 'Working Space' system.

### **Building envelope and bioclimatic conception**

The choices made during the development of the construction system take into account very demanding environmental criteria. For Switzerland, this challenge resonates with the vision of the 2000-watt society, developed by the domain of the Swiss Federal Institutes of Technology. The very issue of this concept is a balanced management of resources, in particular an optimal building design in terms of energy efficiency and priority use of renewable energy (Novatlantis, 2011). In order to reduce the operation energy needs, the design of the 'Working Space' system is mainly based on a bioclimatic approach, using the opportunities of local climatic conditions.

In winter, the high-performance building envelope reduces heat loss and thereby the energy consumption for heating. The use of radiators fitted with thermostatic valves ensures maximum responsiveness of the system, which automatically adapts to the amount

of solar and internal gains. The heat distribution is simply connected to the existing production, without inducing an increase of the power installed.

In summer, the functioning relies on a restriction of solar gains by means of fixed and mobile solar protections, along with a maximisation of natural lighting, free natural ventilation and passive night cooling. In addition, vegetated surfaces located in front of the glazed façade contribute to urban biodiversity, but also to summer heat reduction by natural evapotranspiration (Figure 3). This results in an optimal quality of the indoor climate, with very little energy cost.

Furthermore, the system is composed of a timber structure, and all relevant components consist of materials with very low embodied energy. The system therefore has an excellent life cycle assessment.

Last but not least, the system puts emphasis on renewable energy production, in particular by integrating a vast surface of photovoltaic roof panels.

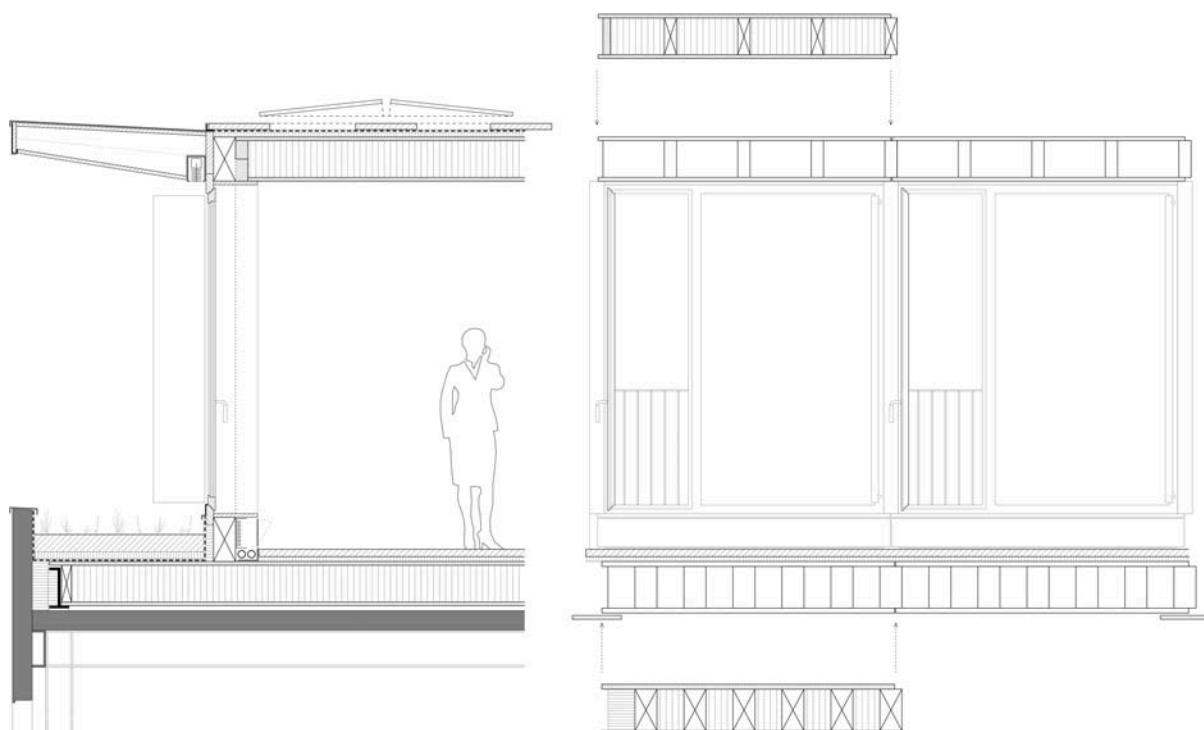


Figure 3. Cross sections through the system's envelope showing its construction principles.

## Assessment

### ***Methodology and reference standards***

The 'Working Space' system simultaneously intends to reduce embodied energy in the construction phase, to minimise operating energy and to produce renewable energy in the same building. An energy balance was carried out to assess how successfully these criteria were met. It bases on a pilot project currently being conducted in downtown Lausanne, Switzerland, comprising about 40 workspaces. This first application of the system plans a vertical extension of an existing office building from the 1970s, with an energy reference area (ERA) of 730 m<sup>2</sup>. The average lifespan of the construction was set at 60 years, according to the common practice.

Calculation of embodied energy uses the Swiss life cycle assessment (LCA) Database of Construction (KBOB, 2016). Regarding operating energy needs, results were derived from

energy balances based on the Swiss technical standard SIA 380/1 (SIA, 2016). Photovoltaic power generation was determined on the basis of actual data from the system operator. Finally, all these gross values were converted in non-renewable primary energy (NRE), using factors given by the Swiss LCA Database of Construction.

Reference standards for NRE requirements are drawn from SméO, a holistic sustainability assessment tool, tied to the objectives of the 2000-watt society (Ville de Lausanne & al., 2014).

### ***Energy efficiency and ecological construction***

As illustrated in Table 1, results show that the amount of embodied energy in construction materials is about 10% lower than the target value given by SméO / 2000 W. This is mostly due to an abundant use of wood in the structural system and to the care taken in choosing finishing materials. The latter all conform to the Minergie-ECO label, a very high standard of ecological construction in Switzerland.

Table 1. Estimated performances in non-renewable primary energy (NRE), rounded values.  
(Sources: construction: EPFL/LAST, heating: Efin'Art sàrl, PV power generation: SI-REN SA, Lausanne)

WORKING SPACE - ENERGY BALANCE	final energy [kWh/m <sup>2</sup> y]	conversion factor [KBOB 2016]	primary energy NRE [kWh/m <sup>2</sup> y]	total amount NRE [kWh/m <sup>2</sup> y]	target value NRE [kWh/m <sup>2</sup> y]	limit value NRE [kWh/m <sup>2</sup> y]
<b>construction</b>						
materials	embodied energy		32	51	36	45
photovoltaic roof	embodied energy		19			
<b>heating</b>	district heating [waste]	20	0.45	9		
domestic hot water	district heating [waste]	7	0.45	3	1	
<b>heating savings</b>	<b>insulation existing roof</b>	<b>-23</b>	<b>0.45</b>	<b>-11</b>		
<b>electricity</b>					83	103
consumption	Swiss consumer mix	22	2.52	56	<b>-307</b>	
<b>generation [PV]</b>	<b>Swiss consumer mix</b>	<b>-144</b>	<b>2.52</b>	<b>-362</b>		

If the embodied energy included in the large photovoltaic roof is added – which is far from negligible – the total amount of NRE exceeds the limit value by 10%. However, the roofing system is an active device producing renewable energy, and this worsening of the grey energy balance is largely offset by corresponding power generation, as will be outlined below.

Regarding heating and domestic hot water, the energy demand of the extension itself is very low, given the high-performance insulation and the smart management of passive solar gains. Furthermore, considerable heating savings result directly from the vertical extension, as this leads *de facto* to reduce the energy loss of the existing flat roof by 100%. If this is also taken into account, the heating energy balance practically tends to be neutral.

Finally, the electricity demand is again widely offset by photovoltaic power generation. In the end, this pilot project shows a negative energy demand. In other words, it is a positive-energy building.

In summary, each square metre of usable area developed with the 'Working Space' extension system induces one square metre of insulated roof on the existing building, thus reducing its heating demand, and produces another square metre of solar energy production on the new roof, resulting in a very favourable energy balance – and that without wasting any square metre of building land.

Last but not least, the impacts of project-induced mobility are currently being assessed. If the building sector indeed accounts for 40 % to 50 % of total energy consumption in Switzerland, mobility stands for more than 30 % (Jochum, 2004). In this

particular case, ideal conditions exist *a priori*: a strategic location in the city centre, linked with close access to public transportation and short distances between place of residence and place of work. The results will shortly be presented and put into perspective.

### Conclusion and outlook

As a holistic concept, 'Working Space' addresses sustainability issues at different levels. On an urban scale, it enables densification within built up areas by developing new workplaces, in particular close to public transportation. At the building scale, it integrates structural and technical requirements into a coherent architectural design, especially in terms of bioclimatic building envelope and active photovoltaic roofing system. At the construction detail level, it uses materials with an environmental friendly life cycle assessment.

The pilot project currently being conducted in Lausanne (Figure 4) will allow testing the results of the research project and measuring the actual post-occupancy performances of the building. It will also enable to verify the technical and economical relevance of the system, especially in terms of prefabrication, transport and assembly of large elements in a dense urban context and on a building in operation. Lastly, psycho-social aspects such as user acceptance, indoor comfort and bioclimatic operation based on user needs will also be studied with the aim of optimising the system. Further developments could also lead to the application of the system to other functions, e.g. for school buildings.

This interdisciplinary research project has allowed for the development of an innovative modular timber construction system for the extension of office buildings and its theoretical contribution to the long-term vision of the 2000-watt society. Integrating ecological criteria as essential components of any architectural design, 'Working Space' is part of a global contribution towards a more sustainable built environment.



Figure 4. View of the pilot project being conducted in Lausanne, Switzerland.

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## References

- Comtesse, X. (ed.) (2008). *Elever la ville. Contribution et débats sur la densification urbaine en Suisse romande*. Zurich: Avenir Suisse & Ecublens: Revue Tracés
- HSLU/CCTP, Kompetenzzentrum Typologie & Planung in Architektur; HSLU/ISE, Institut für soziokulturelle Entwicklung & EPFL/LAST, Laboratoire d'architecture et technologies durables (2016). *Das modulare Bausystem Living Shell. Qualitätsvolle Verdichtung durch Ausbau und Sanierung von Dächern und Fassaden*. Zurich: vdf, Hochschulverlag an der ETH Zürich
- Jochem, E. (ed.) (2004). *Steps towards a sustainable development. A White Book for R&D of energy-efficient technologies*. Zurich: CEPE, Centre for Energy Policy and Economics & Novatlantis, Sustainability at the ETH Domain
- KBOB, Conférence de coordination des services de la construction et des immeubles des maîtres d'ouvrage publics (2016). *Données des écobilans dans la construction 2009/1:2016*. Bern: BBL, Swiss Federal Office for Buildings and Logistics
- Novatlantis, Sustainability at the ETH Domain; SFOE, Swiss Federal Office of Energy & SIA, Swiss Society of Engineers and Architects (2011). *Smarter Living. Moving Forward to a Sustainable Energy Future with the 2000 Watt Society*. Bern: BBL, Swiss Federal Office for Buildings and Logistics
- OFS, Office fédéral de la statistique (2016). *Statistique de la superficie 2004/09*. Neuchâtel: OFS
- OFQC, Office fédéral des questions conjoncturelles (1991). *Documentation sur le parc des bâtiments en Suisse*. Bern: OFQC
- Rey, E. (2011). (Re)construire la ville autrement. *Tracés*, 17, pp. 7-10
- Rey, E. (2012). 'Swisswoodhouse, an innovative concept for sustainable modular housing', in *PLEA Conference Proceedings*. Lima, 7-9 November 2012
- Rey, E. (2013). 'Retour en ville', in Rey, E. (ed.), *Green Density*. Lausanne: PPUR, pp. 9-10
- Rey, E. & Graf, S. (2015). 'Swisswoodhouse, innovative experimentation in sustainable modular housing: from interdisciplinary research to post-occupancy monitoring', in *PLEA Conference Proceedings*. Bologna, 9-11 September 2015
- SIA, Swiss Society of Engineers and Architects (2016). *SIA 380/1:2016. Besoins de chaleur pour le chauffage*. Zurich: SIA
- Tulamo, T-S. (ed.) (2014). *smartTES. Innovation in timber construction for the modernisation of the building envelope. Book 2. TES Extension*. Helsinki: Aalto University School of Arts, Design and Architecture, Department of Architecture & Munich: Technische Universität München, Chair for Timber Architecture
- Ville de Lausanne, Section durabilité & économie de la construction; EPFL/LAST, Laboratoire d'architecture et technologies durables & Etat de Vaud, Service immeubles, patrimoine et logistique (2014). *SméO. Société à 2000 watts*. Lausanne: Ville de Lausanne & Etat de Vaud
- Williams, K. (2000). 'Does Intensifying Cities Make them More Sustainable?' in Williams, K., Burton, E. & Jenks, M. (ed.), *Achieving Sustainable Urban Form*. London: Spon Press, pp. 30-45



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Sustainability, government laws and the real estate market in São Paulo - Brazil

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**Abstract:** In São Paulo, Brazil, the construction of buildings follows various legislations. These laws change according to the human need. This is a conflict between human sustainability and real estate market. In this research was observed the evolution of the legislation, the human needs of insolation in the environments (health) and the evolution of the real estate market. Considering insolation, the code of works 1929 was more restrictive than the code of works 1992, indicating the return of some aspects of environmental comfort of this code. Considering the real estate market was verified the evolution of the height of the constructions and the maximum financial use of the site that considers little the questions of sustainability. The case study identified two vertical housing complexes. It is concluded that the aspects of thermal comfort (insolation) that remain on the responsibility of construction technicians are not met when the real estate market dictates the rules. It is necessary to review the town planning and construction legislation in order to establish rules that deal with the environmental conditions of buildings implantation to guarantee the insolation of the environments and the health of the human being.

**Keywords:** Sustainability, government laws, and the real estate market.

### Introduction

The city of São Paulo was developed from the miscegenation of beliefs, ethnicities, cultures and peoples. It is currently one of the largest agglomerations (conurbations) in the world (SÃO PAULO, 2010)

The result of this agglomeration was the disorderly growth of the city, the increase of vertical housing complexes as an alternative to the urban conflicts related to the security and the valorization of the land. Considering the health of the population, there was an increase in pollution and respiratory diseases, according to Kanarek (2005) in 2005, 30% of the Brazilian population already had allergic rhinitis, while Capelo (2012) described that in 2012 this number increased to 45%.

It is necessary to verify the connection between population densification and the increase of cases of respiratory diseases in urban centers. It can be said that the city of São Paulo always presented legislations and norms for the construction, but the use of these norms did not guarantee a good condition of insolation of the buildings and the housing units.

## **Urban Development and legislation in the city of São Paulo - Brazil.**

The urbanization of the city of São Paulo has evolved following urban control instruments. These instruments include, among others, the constructive capacity of the land, the conditions of use, the regions for each occupation and the specifications for each type of construction.

Nobre (2004) divided the urbanistic instruments into six main periods that determined the way of building in São Paulo: (i) Until 1934; (ii) from 1935 to 1957; (iii) from 1958 to 1972; (iv) from 1973 to 1986; (v) from 1987 to 2002; and (vi) from 2003 to 2013; presented succinctly in the sequence.

Until the first period (i), the height limit of a building was directly related with the width of the street, considering the Postures Code (1886) and the State Sanitary Code (MORAES, 2013).

The first Code of Works of the Municipality of São Paulo, known as the "Arthur Saboya" Code, was created with the Law no. 3,427 in 1929 and established the height limit according to the width of the streets and allowed, for the first time, the increase of heights when there was a setback from street alignment .

In the second period (ii) from 1935 to 1957, it was kept the basic idea of the relationship between height of buildings and width of the street and the minimum insolation period of 3 hours (the shortest day of the year) adding also the allowance of frontage setback.

The possibility of height elevation was then created, mainly in the center of the city, where the American pattern aligned with the borders and the street was determinant, according to Lefreve (1951, apud MORAES, 2013). This standard was extended to other areas of the city with Law no. 3,571 / 1937, which allowed the concentration of high-rise buildings (verticalization) for residential use. This period ended with the creation of Decree no. 3,205 / 1956, which made it compulsory to use elevators, which made it possible to increase the number of buildings in the areas near the center.

In the third period (iii), from 1958 to 1972, the first significant change was related to the verticalization of the building that became a function of the occupancy rate compared with the size of the land. It was established by Law no. 5,261 / 1957, the maximum utilization coefficients (CA), as well as their conditions of use.

Law no. 6,877 / 1966 changed the utilization coefficients (CA) to six in all areas of the city. This change generated housing problems, mainly concerning the healthiness of the building, since, setbacks were not guaranteed and openings were not properly sized for housing. The same Law modified the concept of insolation, which should be made in relation to the floor area. It was also taken into account that this area should consider the projection of the sun between 9 A.M. and 3 P.M..

After 1966, due to the speculation of the real estate market, several modifications in the construction regulations continued to change, mainly, the coefficients of utilization or its places of application. Producing almost two hundred norms until the beginning of the decade of 1970, this caused an overlapping problem in places of greater economic interest.

In the fourth period (iv), from 1972 to 1986, Law no. 7805/1972 known as the Zoning Law, which for the first time covers the whole city and establishes zones of use differentiated by their characteristics and constructive potentials, as well as setbacks, templates and occupancy rates for each of these zones. During this period, in the midst of so many revisions, the residential real estate market began to use the maximum utilization

coefficients, which generated free areas within the lot. The verticalization has hit new neighborhoods.

The beginning of the fifth period (v), from 1986 to 2002, was marked by the approval of the Urban Operations Act, which emerged from the market pressure to increase the city's constructive potential (NOBRE, 2004). However, the locations where verticalization was intended were not met and the already verticalized but high profitability sites were more densely packed. The verticalization extended to places farther from the center and increased in already densely populated places.

In 1992, the new Code of Works and Buildings of the city of São Paulo (COE) was approved, which defined, in item 10, the conditions of implantation, aeration and insulation of buildings. It is important to highlight the new concept of sunshine indexes adopted from the "A" aeration band and the "I" insulation band, which aimed to guarantee insulation and ventilation through the spacing between buildings (setbacks).

The period ended with the creation of the Strategic Master Plan, in 2002, predicting the creation of other urban planning mechanisms contemplated in later period.

Initiated in 2002, the sixth period (vi) was characterized by the creation of the City Statute, which immediately generated a new Strategic Master Plan (PDE). It proposed, among other functions, to combat the inequality in the city, with urbanization of the peripheries, recovery and environmental protection; population densification in areas of good infrastructure and job supply; and items to make social interest housing feasible without hurting previous questions. According to Moraes (2013), two years after the Zoning alteration, allied with the construction growth, there was a great increase in the number of buildings in the city, and also the emergence of the condominium-club concept, which favored the use of vacant lots located in manufacturing or peripheral areas of the city.

Figure 1 shows the neighborhoods affected by verticalization in the city of São Paulo.

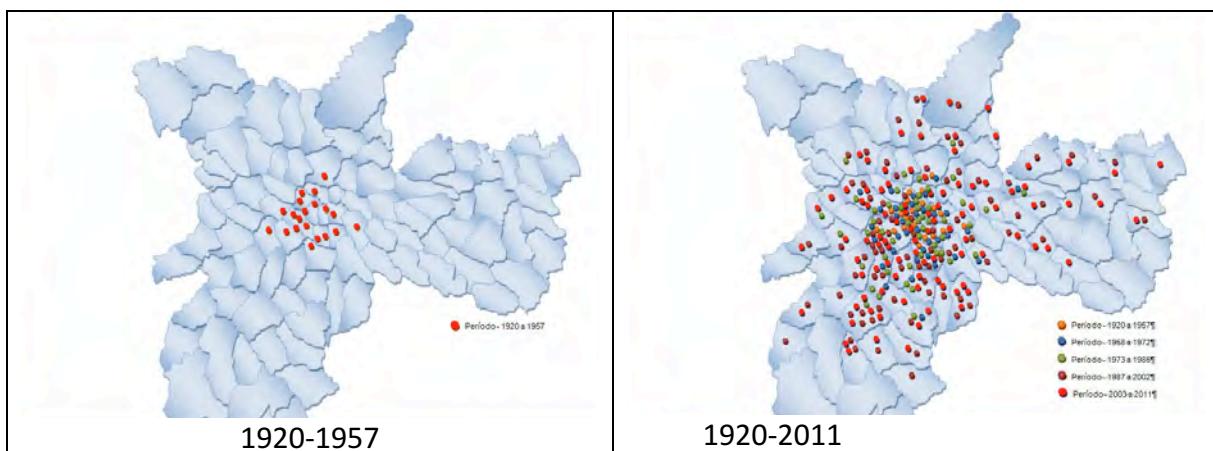


Figure 1 - Expansion of verticalization by neighborhoods in the city of São Paulo. Source: Moraes (2013).

### Case Study

A case study was carried out which comprised two cases and three controlling criteria of the laws of 1992, 2004 and 1929.

The Code of Works (CO,1929) established, with regard to this research, the need for three hours of daily sunshine. Subsequently, the correlations between height and distances between buildings were adopted, culminating in COE (1992).

Comparing the COE (1992) to the CO (1929), it seems that a conflict between standards was found, in which the most protective fundamental right for the user of the building, that is, the right to healthy housing, should prevail.

This confrontation will be evidenced by the fact that CO (1929) is more restrictive than COE (1992) and, in order to enable such analysis, the following criteria were used:

- A. Verify if the buildings meet the minimum COE setbacks (1992);
- B. Verify if the buildings meet the minimum setbacks of the Zoning Law (2004);
- C. Check if, at the winter solstice, all apartments receive at least three hours of sunshine on the facades of the dormitories, between 10 am and 2 pm CO (1929)

After that, when the criteria A, B and C were confronted, it could be confirmed whether there was any damage to the user's health with the end of CO (1929).

In order to compare the criteria, after having scaled the volume of the housing complexes, a simulation was carried out in Heliodon, in order to evaluate the performance on the day of the winter solstice, thus concluding, which criterion is more restrictive and should therefore be adopted.

**CASE 1** (Figure 2): Residential complex with project approved after the Zoning Law of 2004. It has 4 towers with 26 floors, ground floor, duplex cover and underground parking. With the headroom of approximately 3.00 meters, its estimated height is 88 meters. The floor area is 362 m<sup>2</sup>, with 4 residences per floor. It has openings of interest, that is, belonging to "Group A", on the two largest faces of the buildings.

**CASE 2** (Figure 4): residential complex with an approved project between COE 1992 and the Zoning Law of 2004. It has 28 towers with 16 floors and ground floor. With the headroom of approximately 2.85 meters, its estimated height is of 49 meters. The area of the pavement is 305 m<sup>2</sup>, being 4 residences per floor. It has openings of interest, that is, belonging to "Group A", on the four sides of the building.

For the analysis of criteria A and B, the values of the "A" and "I" bands and "R" stepback were calculated, represented graphically in Figures 2 and 4 below in the colors blue, green and red, respectively.

With regard to Case 1, it can be observed in Figure 2 that the criteria A and B were completely satisfied.

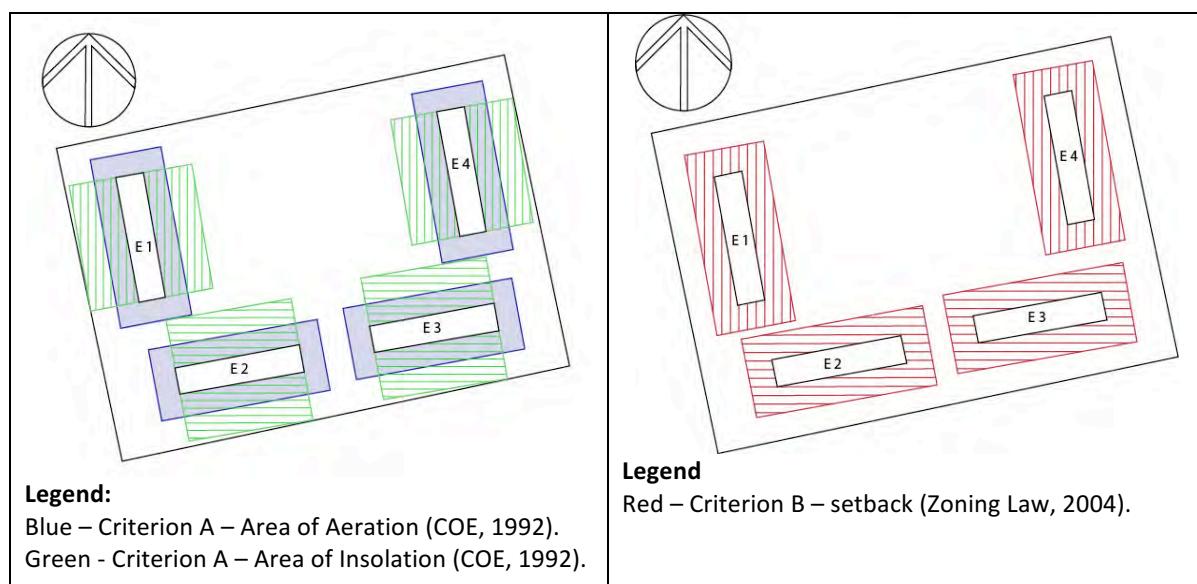


Figure 2 - Case Study 1: Analysis of criteria A and B. Source: Authors.

To verify the criterion C, the simulation was performed in Heliodon, Figure 3 shows the result of the Case 1 study.

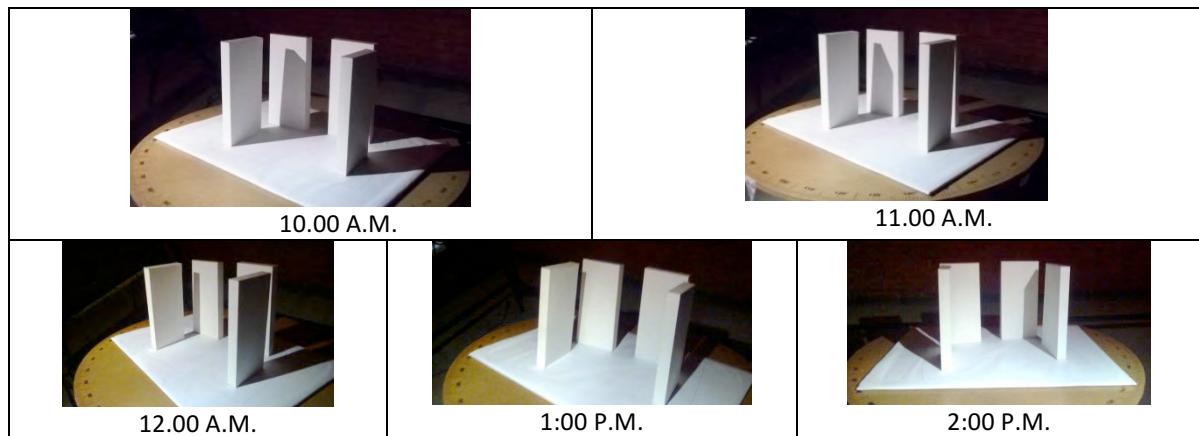


Figure 3 - Case Study 1: Analysis of Criterion C. Source: Authors.

Regarding criterion C, on the faces of interest of the buildings E2 and E3 positioned to the south there wasn't solar radiation on the day of winter solstice at any time. On the facades of interest of the E1 and E4 buildings positioned to the west and east, respectively, there wasn't solar radiation for three hours between 10 a.m. and 2 p.m. as requested by CO (1929).

In Case 2, it can be seen in Figure 4 that the criterion A was partially met, since, despite the compliance with the values for "A" band, without the overlapping of them, it occurred the advance of "I" bands over "A" bands, fact restricted by COE (1992). For criterion B, it has been fully complied despite the apparent proximity between some buildings

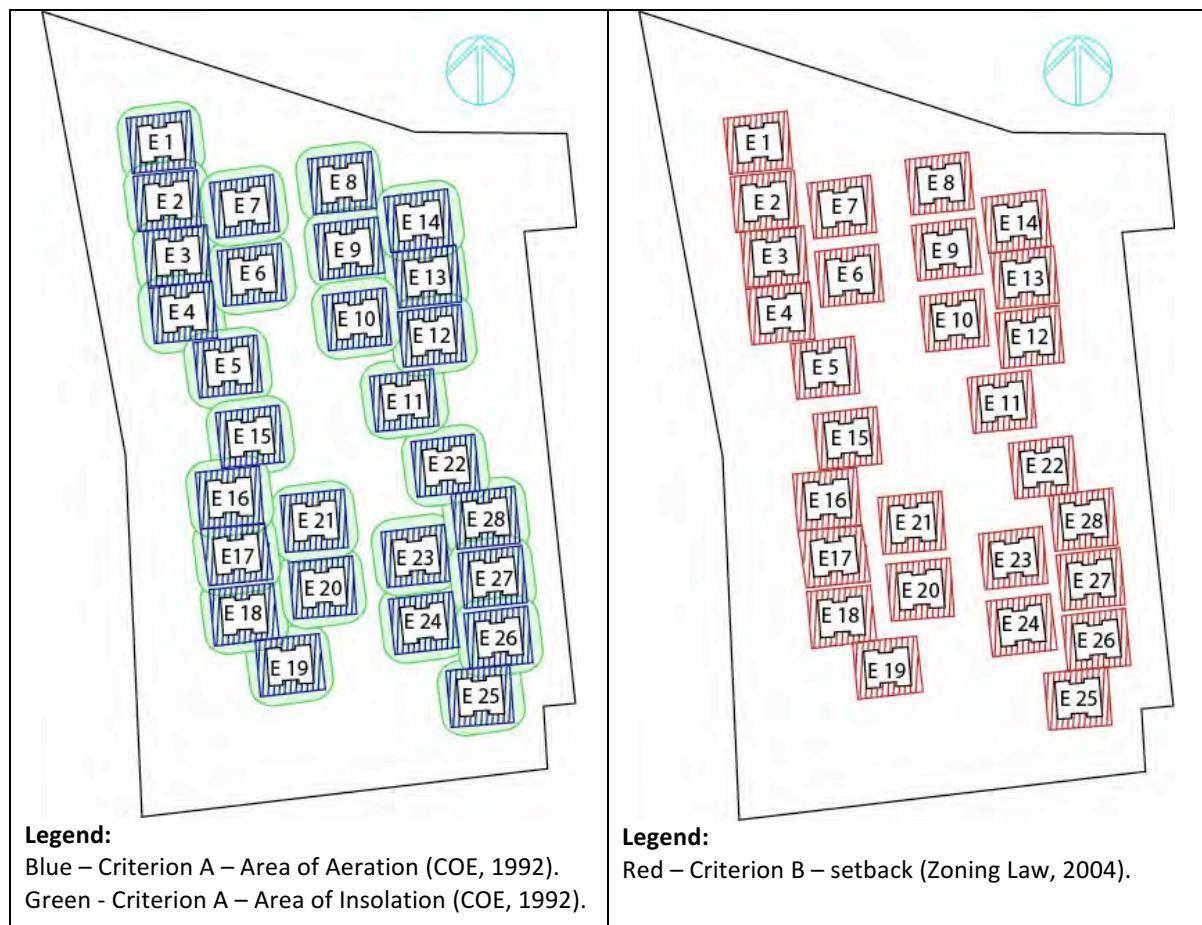


Figure 4 - Case Study 2: Analysis of criteria A and B. Source: Authors.

Considering Criterion C, shown in Figure 5, only the north façades of buildings E1, E7, E8 and E14 received solar lighting directly between 10 a.m. and 2 p.m.. All south facades were free of solar incidence on the day of winter solstice. The other façades received an incidence lower than necessary for the criterion and, for that, were not approved.

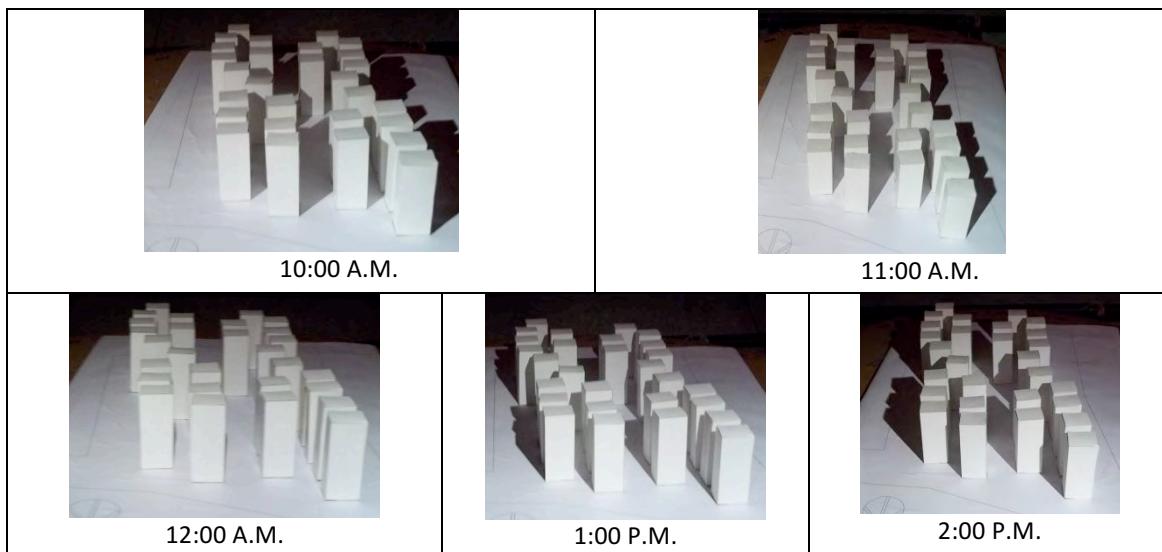


Figure 5- Case Study 2: Analysis of Criterion C. Source: Authors.

### Conclusions/Discussions

It was observed the verticalization of São Paulo in six periods, being verified the change of legislation, as well as the emergence of the condominium-club concept, a response of the real estate market the Zoning Law of 2004, consonant to a response of the society in the search for Safety and quality of life.

A case study was carried out on two vertical sets of buildings being one built after the Zoning Law and another one from the 1990s.

It was found that although the concept of club condominium and the application of the Law have improved the conditions of insolation of apartment dormitories, when applying the legislation of 1929 it was verified that the minimum of three hours of insolation has not been proven in all the dormitories.

There is in the Federal Constitution (1988) the prevalence of human rights, that is, any norm that guarantees greater protection to the individual must be ensured. From this understanding, the right to healthy housing should be part of the right to housing itself, constitutionally foreseen.

A more protective standard should always be observed, which in this case is CO (1.929) [represented by criterion C], but still respecting the COE (1992) [represented by criterion A] and the Zoning Law (2004) [Represented by criterion B]. With this finding, it is necessary to discuss more about the legislation and the consequences that can occur in the quality of life of users.

### References

- BRASIL. Constituição da República Federativa do Brasil de 05 de outubro de 1988. Brasília: Câmara dos Deputados, Edições Câmara, 1988.
- CAPELO, R. **Comum no inverno, rinite pode comprometer o desempenho profissional**. Linhares. 2012. Disponível em: <<http://joaodaniel.com/materia-e-artigo.php?id=10>>. Acesso em: 21 set. 2012.
- KANAREK, D. **Saiba por que há tantos casos de rinite alérgica e proteja seu filho**. 2005. Revista Crescer. São Paulo, edição 139, jan. 2005.

MORAES, S. R. C. de. **O Arquiteto e o Mercado Imobiliário Residencial na Cidade de São Paulo no século XXI.** 2013. Tese (Doutorado) - Faculdade de Arquitetura e Urbanismo, Universidade Presbiteriana Mackenzie, São Paulo, 2013.

NOBRE, E. A. C. **Novos instrumentos urbanísticos em São Paulo: limites e possibilidades. Seção Técnica de Programas de Revitalização.** Departamento do Patrimônio Histórico. Prefeitura do Município de São Paulo. São Paulo, 2004.

SÃO PAULO (Município). Lei n. 3.427 de 19 de novembro de 1929. Código de Obras Arthur Saboya. **Diário Oficial**, São Paulo, 19 nov. 1929, f. 1.

SÃO PAULO (Município). Lei n. 3.571 de 7 de abril de 1937. Declara aplicáveis às avenidas Paulista, Higienópolis, Angélica, Pedro I, Pompéia e rua Maranhão às exigências do artigo 40 do Ato n. 663/1934. **Diário Oficial**, São Paulo, 7 abr. 1937, f. 1.

SÃO PAULO (Município). Decreto n. 3.205 de 23 de agosto de 1956. Regulamenta a instalação e funcionamento de elevadores e dá outras providências. **Diário Oficial**, São Paulo, 24 ago. 1956, f. 73.

SÃO PAULO (Município). Lei n. 5.261 de 4 de julho de 1957. Estabelece coeficiente de aproveitamento de lotes, densidade demográfica, área mínima de lote por habitação e área mínima de espaços livres, e dá outras providências. **Diário Oficial**, São Paulo, 5 jul. 1957, f. 5.

SÃO PAULO (Município). Lei n. 6.877 de 11 de maio de 1966. Dispõe sobre os índices máximos de aproveitamento dos terrenos para fins de edificação e reserva de espaços livres, nos arruamentos, e dá outras providências. **Diário Oficial**, São Paulo, 12 mai. 1966, f. 1.

SÃO PAULO (Município). Lei n. 7.805 de 1 de novembro de 1972. Dispõe sobre o parcelamento, uso e ocupação do solo do município, e dá outras providências. **Diário Oficial**, São Paulo, 3 nov. 1972, f. 1.

SÃO PAULO (Município). Lei n. 11.228 de 25 de junho de 1992. Dispõe sobre as regras gerais e específicas a serem obedecidas no projeto, licenciamento, execução, manutenção e utilização de obras e edificações, dentro dos limites dos imóveis, revoga a Lei n. 8.266/1975, com as alterações adotadas por leis posteriores, e dá outras providências. **Diário Oficial**, São Paulo, 26 de jun. 1992, f. 1.

SÃO PAULO (Município). Decreto n. 32.329 de 23 de setembro de 1992. Regulamenta a Lei n. 11.228/1992 - Código de Obras e Edificações, e dá outras providências. **Diário Oficial**, São Paulo, 24 set. 1992, f. 1.

SÃO PAULO (Município). Lei n. 13.430 de 13 de setembro de 2002. Da conceituação, finalidade, abrangência e objetivos gerais do Plano Diretor Estratégico. **Diário Oficial**, São Paulo, 14 de set. 2002, f. 1.

SÃO PAULO (Município). Lei n. 13.885 de 25 de agosto de 2004. Estabelece normas complementares ao Plano Diretor Estratégico, institui os Planos Regionais Estratégicos das Subprefeituras, dispõe sobre o parcelamento, disciplina e ordena o uso e ocupação do solo do município de São Paulo. **Diário Oficial**, São Paulo, 6 de out. 2004, f. 1.

SÃO PAULO TURISMO S/A. **História de São Paulo.** São Paulo. 2010. Disponível em: <<http://www.cidadedesaoporto.com.br/a-cidade-de-sao-paulo>>. Acesso em: 14 set. 2012.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## MORE VERSUS BETTER: exploring the tension between quality and quantity in housing, and the opportunities offered by alternative approaches

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**Abstract:** This paper translates the seven goals of the Wellbeing of Future Generations (Wales) Act into an agenda for housing. It recaps the findings of the recent More | Better report (2017), which concluded that there is no single silver bullet to ‘solve’ the housing crisis in Wales, but that higher quality homes could be achieved through a combination of innovative delivery pathways and construction techniques, along with a broad range of other benefits. However, the depressed Welsh housing market creates a particular tension between the need for *more* housing and drivers for *better* homes. The paper identifies ways in which approaches that focus on ‘better’ might also deliver ‘more’ in economically challenging areas, both within Wales and more widely. There then follows a discussion of the catalysts for such a ‘step change’ in housing quality and quantity. The paper concludes with an account of the next steps that are currently being taken in Wales, through the actions of the Innovative Housing Programme.

**Keywords:** housing, housing crisis, housing supply, construction techniques

### Introduction

*Homes for Today and Tomorrow* was published in 1961. In that moment, it was considered “timely to re-examine the kinds of homes that we ought to be building, to ensure that they will be adequate to meet the newly emerging needs of the future, as well as basic human needs which always stay the same.” The landmark report proposed space standards (later termed ‘Parker Morris’) that were mandated for all new social housing in the UK by the end of the 1960s, but abolished just over a decade later in 1980. Recently these standards have risen back to prominence in a number of emerging housing standards, alongside the same desire to build new housing that is truly forward thinking...

### WFGA: a Welsh perspective on the future of housing

Existing and emerging drivers for ‘better’ housing include increasingly stringent limits on energy consumption and CO<sub>2</sub> production, and an increasing aspiration for quality of placemaking, design, workmanship, fuel efficiency and longevity. The Well-being of Future Generations Act (WFGA) came into force in Wales during April of 2016, and demands that all future Welsh Government (WG) activities prioritise long term gains over short term expedience. When we were commissioned by WG to investigate the potential of alternative approaches to inform and improve housing delivery in Wales, one of our first actions was to translate the new Act’s seven well-being ‘goals’ into a set of aspirations that are specific to new housing:

<b>A globally responsible Wales</b>	Setting higher standards – reduced carbon footprints and energy-positive communities
<b>A prosperous Wales</b>	Developing an integrated all-Wales supply chain using local resources and a sustainable economy
<b>A resilient Wales</b>	Future proofing with long term flexibility, adaptability, ecological value and climate resilience
<b>A healthier Wales</b>	Reduced pressure on the health service through homes that promote physical and mental wellbeing
<b>A more equal Wales</b>	Eliminating household poverty by delivering affordable housing for all
<b>A Wales of cohesive communities</b>	Stronger neighbourhoods that support co-housing, self-build and cohesive communities
<b>A Wales of thriving culture and language</b>	Promoting diversity through Wales' unique cultural heritage, context and landscape

Figure 1. Aspirations for housing in Wales, drawn from the Well-being of Future Generations (Wales) Act.

### The MORE | BETTER study

There is a clear need for diverse, high quality, low energy housing in Wales that is not being met, and is not likely to be met through established methods (PPIW, 2015). Key factors limiting the supply of new homes include the availability and financial value of land, the cost of building new homes to contemporary standards, and the limited flexibility of approaches adopted by a relatively small number of national housebuilders, who dominate the supply of housing in the UK, but are increasingly unlikely to operate throughout much of Wales. Less is known by the industry at large about the range of alternative approaches to house-building that exist in the UK, some established and others that are emerging. Some of these approaches relate to construction techniques, others to delivery pathways (including commissioning and procurement). Each has particular benefits and limitations. Together, they could significantly increase our national capacity to build more homes, better.

The More | Better report (Green et al., 2017) was commissioned by Welsh Government's Homes and Places division, to inform decision-making by commissioners of housing in Wales. It provides thirteen themed essays<sup>1</sup> from expert contributors coupled with a comparative study of thirteen 'best practice' case studies. Together, they describe the complexities inherent in housing delivery, and analyse the potential of alternative approaches to realise wider benefits. The report concludes that there is no single silver bullet to 'solve' the housing crisis, but that *more, better* housing could be produced through a combination of innovative delivery pathways and construction techniques, along with a wide range of socio-economic and environmental benefits. The report was presented at the Innovative Housing Conference in Cardiff (CHC, 2017) and accompanied an announcement from Cabinet Secretary for Communities and Children Carl Sargeant that WG will invest £20m in an Innovative Housing Programme, commencing in 2017 with support for a first phase of innovative new homes across Wales.

<sup>1</sup> Themes include Standards (Passivhaus, FEEs / zero carbon, Living Building Challenge), Thinking Local (cooperation makes housing better, better buildings better resources), Making Places (accommodating growth, edge of settlement) and Building Alternatives (commercial alternatives, modular, open source and DDM).

## Findings 1: exploring BETTER | benefits and considerations

The More | Better project assessed a range of alternative approaches that included both delivery pathways and construction techniques. Each approach was found to have distinct limitations and potential benefits (fig. 2, below). Some benefits impact on project **delivery** (eg. affordability, reduced site time, fewer defects). Others relate to the development **in use** (eg. reduced fuel bills, lower carbon footprints, energy generation, increased flexibility / adaptability). A third category of **contextual** benefits are wider ranging. Some approaches lend themselves to intensification of existing neighbourhoods, or could deliver higher quality, even zero-defect, building. Locally centred approaches establish opportunities for local training, and promote the use of local materials and resources. Other approaches reduce the specialist skills involved in construction, increasing applicability and putting the power to develop directly into the hands of communities. However, unless these approaches are delivered at scale in a coordinated way, their full benefit will not be realised.

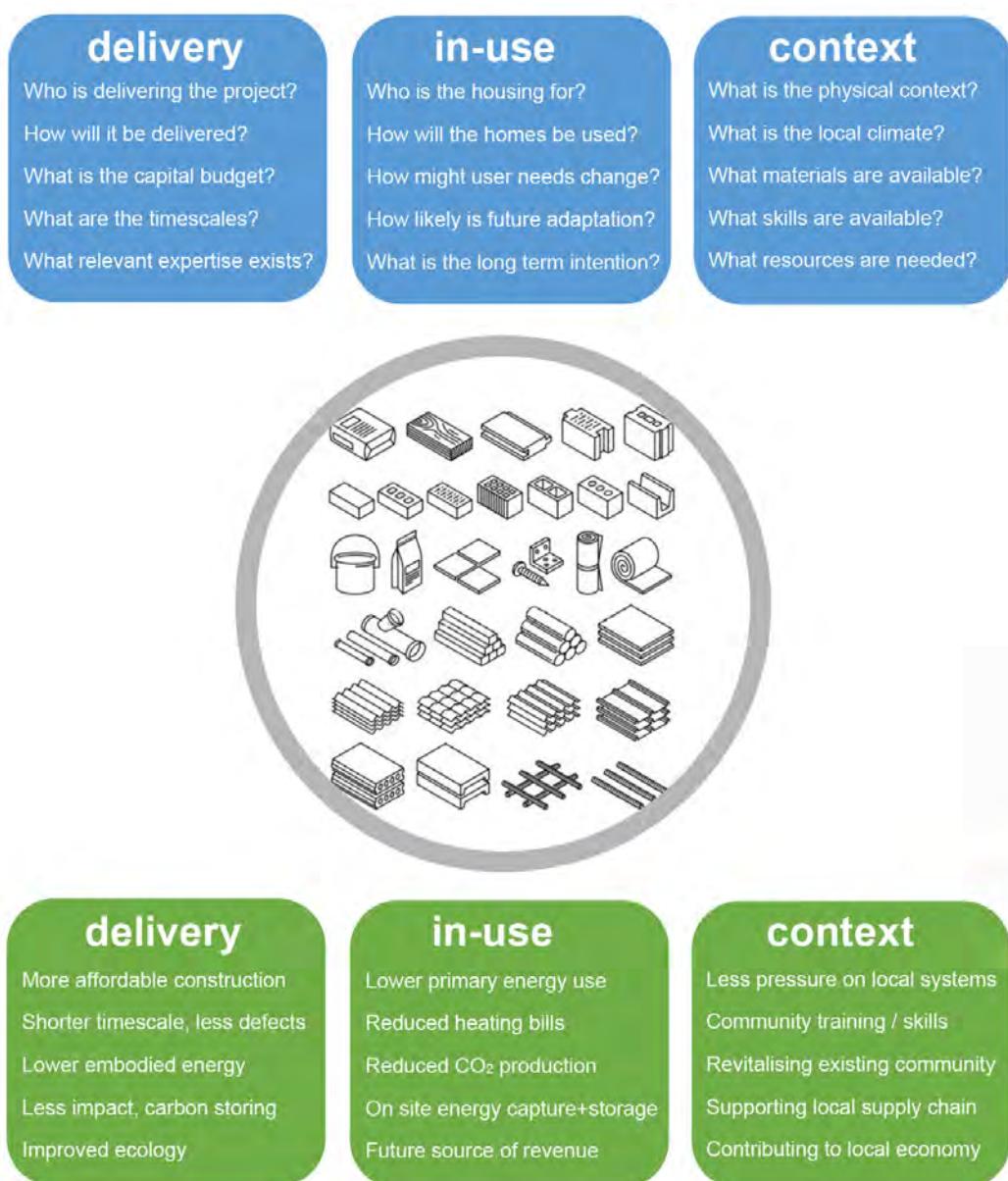


Figure 2. Identification of 'considerations' (blue) and 'benefits' (green) inherent in alternative approaches.

The More | Better project compared seven alternative construction techniques in use. Again, each was found to have distinct limitations and potential benefits, outlined in fig. 3 below. These have been grouped into four broad areas: building performance, design (form), materials, and fabrication. Using this matrix, construction techniques can be assessed for their suitability on a project by project basis.

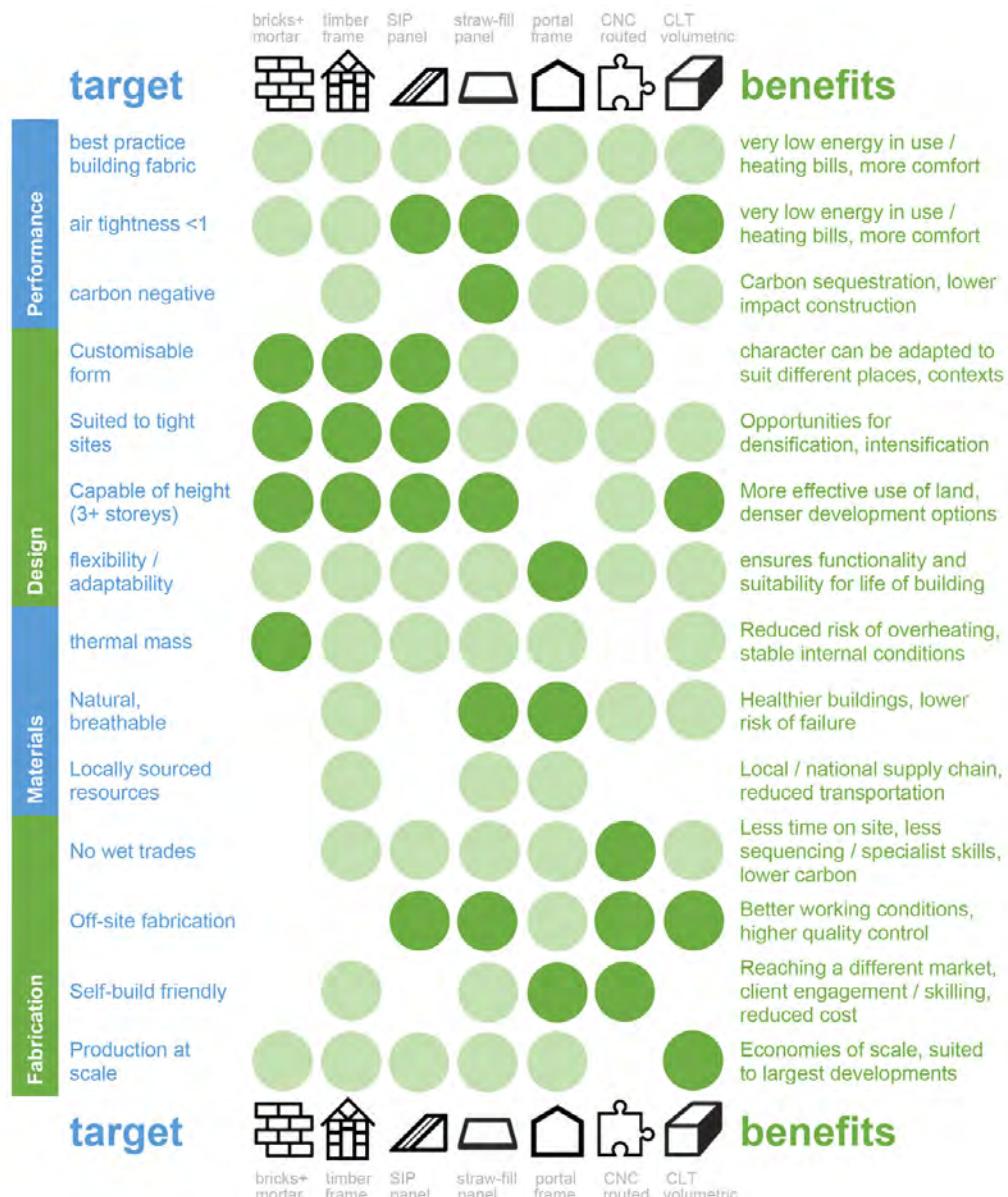


Figure 3. Mapping of 'possible' (light green) and 'delivered' (dark green) benefits by construction technique.

**Performance:** All case studies adopted a fabric first strategy, but to differing degrees. Thermal performance of the building envelope in line with Passivhaus standard are achieved by most of the case studies, typically achieving U-values of at least  $0.15 \text{ W/m}^2\text{°C}$  for walls and roofs, while floors are more varied. Simple, compact building forms are often exploited to make higher standards more affordable. Glazing performance is the most varied, primarily due to the higher cost of better performing glazing products. The case studies all achieved, or propose to achieve, air tightness of no more than 4 air changes per hour@50Pa, but with a considerable range in the values achieved on site. Some construction techniques (SIP, CLT volumetric) are able to guarantee very low air leakage rates. As a result of these measures,

thermal performance is improved between 12% and 35% over target fabric energy efficiency standards (TFFEs, from SAP 2012). When renewables are also taken into account, improvements in performance range between 15% and >100% (TER, from SAP 2015).

**Design:** Some of the case studies utilise construction techniques that are prescriptive in terms of built form. Two of the systems that are suited to self- and community-build projects are limited to simple mono- or dual pitched forms, and have not yet been constructed beyond two storeys. In contrast, other techniques are highly flexible; one case study demonstrates that the same system is capable of two storey row houses, four storeys town houses and ten+ storeys apartment blocks. Techniques based around large modules, including rigid closed panel systems and volumetric systems, are not suited to tight or awkward sites. There are also implications in terms of character; many of the benefits around programme, cleanliness, and carbon are diminished if the buildings are clad in brick or other loadbearing masonry.

**Materials:** Many of the case study approaches utilise timber extensively. A small number maximise the use of local timber, but most rely on imported European timber. For reasons of cost, performance and perception, currently around 85% of UK construction timber is imported (Moore, 2015); manufacturers believe that “home grown timber [is] low quality and that to ensure a reliable supply of products would involve further costs.” (TRADA, 2012). One case study in particular proposes to use low value local timber to produce higher value construction products. Timber is, of course, lauded for its carbon sequestering properties. By combining timber with other carbon-storing materials (eg straw), a number of the case studies achieve carbon negative status. Many of the case studies also emphasise their low cementitious content, resulting in low carbon footprints and reducing specialist skills. Against these benefits, few of the techniques offer much in terms of thermal mass, which will become increasingly important in offsetting cooling requirements as the environment continues to warm. A small proportion of the case studies deliver ‘healthy’ construction and breathable envelopes with anticipated health benefits for users (RCP 2016), but many of them employ rigid petrochemical-based insulants, either for reasons of utility or economy.

**Fabrication:** There have been a number of well-reported forays into housing using modern methods of construction, in particular off-site fabrication. Two of the case studies utilise volumetric construction. Delivered by fabricators seeking to operate at different scales and using different construction techniques, both have significant capacity to operate at scale, and deliver on the benefits expounded by *Rethinking Construction* almost twenty years ago (Egan, 1998), including reduced timescales, fewer (or even zero) defects, higher quality and improved working conditions. However, other fabrication techniques offer different benefits. Self- and community-build have scope to meaningfully reduce capital costs (see following section), while the use of locally sourced materials and resources, including skills training, labour and capacity (for pop up factories, for example) unlocks a range of wider economic benefits. Participatory fabrication also moves housing away from the ‘finished’ architectural product, to better “take into account precisely the unexpected.” (Habraken, 1999)

## **Findings 2: Delivering MORE | cost versus value**

According to BCIS data, the cost of new housing in the UK is among the most expensive in Europe, at around £1050/m<sup>2</sup>. In the drive for better performance, historical social and affordable housing pilot projects attempting to attain higher standards (for example CfSH

level 5/6) have often done so by adapting traditional approaches rather than considering alternatives holistically, which has resulted in untenable cost increases: "...the Code Pilot programme supported the emerging trends and understanding that the cost of delivering zero carbon on site was prohibitive, and could offer serious challenges in both cost and design principles." (BRE, 2013) For lower income communities in Wales, the prospect of purchasing new housing outright at elevated costs is unrealistic. Alternative approaches are needed, that deliver 'better' affordable housing without untenable cost increases.

Capital costs for the fourteen case studies are in the range £500/m<sup>2</sup> to £1500/m<sup>2</sup>. At the lowest end, they did not deliver 'finished' buildings, only shells. Self-build construction dominated the lower cost case studies due to savings on labour (typically 25-45% of total capital costs), but with limited applicability. For the remaining case studies, the capital cost of delivering new homes by a third party remains within conventional margins of £1000/m<sup>2</sup> to £1500/m<sup>2</sup> (tier 1, below). However, it is important to distinguish between cost and value. Alternative approaches should deliver better value homes, without considerably increasing capital costs (tier 2). All of the case studies delivered thermal performance considerably better than compliance with Building Regulations requires, and consequently reduced heating bills. Other approaches propose to increase value through wider benefits such as reduced pressure on local systems (including environment and healthcare), skills provision, increased local employment, and benefits to the local economy.

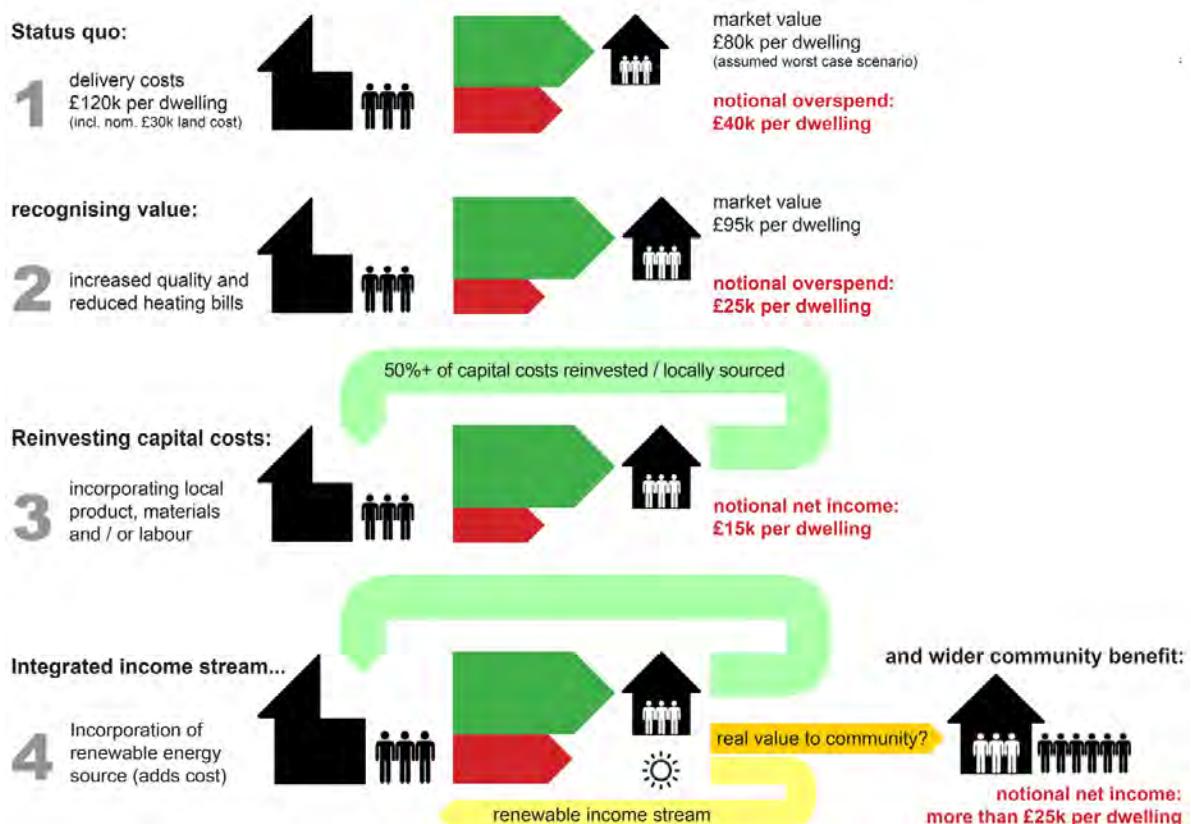


Figure 4. Four tiers of opportunities to impact upon capital costs through the use of alternative approaches.

Perhaps most importantly though, some of the benefits offered by alternative approaches have potential to directly impact on capital costs. Such savings could be generated through reduced labour costs due to self- or community- build. They could also be generated through the use of local materials or resources, whereby capital costs are

reinvested in the local economy (tier 3). However, this would break existing supply chains and necessitate incentivised local resource use, which are not simple changes to make. Finally, tier 4 represents the savings accrued by a number of the case studies, which offset capital costs or rental levels through the inclusion of an integrated renewable income stream (notably photovoltaics). Together these findings suggest that if capital costs can be considered holistically, at the level of the community or even more broadly, there is considerable scope to make new housing more ‘affordable’. In isolation, alternative construction techniques cannot ‘solve’ the affordable housing crisis. However, combined with innovation in delivery, they could produce housing that meets established and emerging aspirations for sustainable, low energy communities, and make better quality homes accessible to households that are currently excluded from them.

### A Step Change

A key assertion of the More | Better report is that Wales should lead the way by placing affordable housing and affordable warmth at the centre of national policy. The WFGA requires that commissioners of housing cease thinking purely in terms of capital costs, and encourage the industry to replace construction that drains resources with buildings that generate them – that are energy positive and carbon negative. This perspective shift requires a fundamental step change in Welsh housing standards and existing / established patterns of housing procurement. To facilitate this step change, the report proposes that Welsh Government:

- task a working group with understanding housing in the context of the WFGA.
- map existing / emerging housing standards against existing performance standards.
- liaise internationally with innovative policy makers, commissioners and practitioners.
- establish an open-access forum for anyone interested in building homes.
- map housing need, supply and opportunities in a transparent, joined-up way.
- nurture industry in Wales with potential to contribute to locally based supply chains.
- explore the intensification of lower density communities in viable locations.

### Conclusions

There is no single silver bullet for the affordable housing crisis. Variations in geography, functional need, socio-economic and cultural settings demand different approaches to ensure ‘appropriate’ responses that make the most of their context. When a new Welsh Housing Standard emerges, it must promote diversity and equality along with sustainability and shared learning. It must be capable of adapting to emerging best practice as well as demanding excellence, to ensure that Wales has a clear pathway forwards, and a means of developing sustainably for the future. These conclusions are equally valid outside of Wales.

By employing alternative approaches, we could be constructing new homes and neighbourhoods in a more contextually appropriate way, with greater long term value. Alternative approaches have the potential to deliver affordable homes in parallel with more established methods, so long as knowledge is shared with commissioners and constructors. Different delivery pathways and construction techniques could lead to more diverse housing that is better quality, more fit-for-purpose, more affordable and more sustainable. Benefits could include the growth of employment, local supply chains, greater long term resilience, and renewable energy infrastructure as a source of income. The creation and maintenance of sustainable communities could provide a new focus for post-industrial settlements, facilitating joined-up development that works at a local level. If we are to rise to the challenge

of the housing crisis by constructing a legacy of homes that future generations consider to be a blessing and not a burden, the correct standards, incentives and monitoring must be put in place to encourage all existing pathways, along with some that do not yet exist.

### Future research

The work conducted to date was conceived as an incubator for further research. The success of More | Better lay in the frank and open contributions offered by a broad church of collaborators. The longer term intent is to deliver a relevant, current resource for key stakeholders involved in housing delivery, working within Wales and elsewhere. For this to happen, the collaborator network must grow, supported by an increase in the depth of investigation, and a rigorous methodology for collaborative analysis. When conducted through an open protocol, this should build the kind of resource that is needed by the industry at this time.

Welsh Government is in the process of supporting the first in a series of phases of innovative housing projects, to learn in a truly open way about innovation, to inform discussion around the type of homes that should be supported in the future, and to direct the shape of the emerging Welsh housing standard. A key next step is identifying, and possibly establishing, the networks that will facilitate the sharing of resources among many industry stakeholders, promoting excellence and innovation throughout the industry. While the conditions that currently preclude more, better housebuilding in Wales are challenging, they are not insurmountable, nor new. As co-founder of RM-JM Sirrat Johnson-Marshall commented, faced with similarly austere circumstances following World War II:

*We are forced to choose between three courses of action: The first is to build only the small amount we're likely to be able to afford. This is to acknowledge defeat. The second is to accept a drastic reduction in space and quality while maintaining the same total. This again is defeat, and why should we accept defeat in this, when we have accomplished so much in other fields – radar for instance, nuclear fission, or jet propulsion? The third course is to approach the whole problem of building afresh, with the objective of devising a fundamentally simpler technique, a technique which will give us greater beauty, comfort and value at a lower cost.*

Johnson-Marshall (1960)

### References

- BRE (2013). WG Code Pilot Programme Technical Report ref. 285-001. BRE  
CHC (2017) <http://chcymru.org.uk/en/view-news/20m-funding-for-innovative-housing-solutions>  
Egan, J (1998). *Rethinking Excellence*. London: The Construction Task Force  
Green E. with Forster W. (2017). *More / better* (report). Cardiff University  
Habraken, N.J. (1999) *Supports: An alternative to Mass Housing*. UK:Urban International Press  
Johnson-Marshall, S. (1960). Quotation, revised interview: *Third Programme*. BBC  
NaSBA (2014). *Survey of self build intentions*. IPSOS MORI / NaSBA  
PPIW (2015). *Future Need and Demand for Housing in Wales*. London: E&F Spon Ltd  
Moore N. (2015) *Timber Utilisation statistics 2015*. UK: Timbertrends  
Royal College of Physicians (2016). *Every Breath We Take* (report). London: Royal RCP  
TRADA Technology (2012) *Future Opportunities for British Timber*. Buckinghamshire: TRADA



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## Study on thermal defects of building envelope of prefabricated concrete shear wall building in cold area

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**Abstract:** In order to meet the needs of building energy conservation and emission reduction and the development of the housing industry, prefabricated building occupies an increasing proportion in the construction of new buildings. The thermal defects of the building envelope have an important influence on the thermal insulation performance and building energy consumption. Compared with the cast-in-place concrete building, the seam structure and material combination of the prefabricated building are more complex, which is more likely to produce thermal defects. Taking the prefabricated residential building of Tianjin Shuangqing Home as the research object, the heat transfer performance and thermal defects of the building envelope of prefabricated building is detected and studied by heat flow meter method and infrared thermography individually. The paper focuses on the thermal defects like thermal bridges in walls, reserved holes to lay the foundation for the design and application of the prefabricated building in cold area.

**Keywords:** Prefabricated residential building, Thermal defects, Performance test, Heat transfer performance of building envelope

### Introduction

With the promotion of the housing industry, the prefabricated building, because of its high quality and precision, fast processing speed, green, gradually replaces the cast-in-place concrete buildings and has become the mainstream of new constructed buildings and the future development direction (Jaillon et al, 2009). The prefabricated building is made up of lots of prefabricated components, which is more complex, in the wall structure and the connecting methods, than cast-in-place concrete buildings. But the current researches on prefabricated building mostly stay on the mechanical properties and seismic performance of joints (Zhao et al, 2014). The study on thermal performance of building envelope is less, and among those studies, most concentrate on the overall heat transfer performance of prefabricated wall panel (Yooprasertchai et al, 2016), research on thermal defects such as the thermal bridge and the wall defects is lack. This paper takes prefabricated shear wall residential building in the cold area as the research object, to study the thermal defects of precast concrete shear wall structure, which provides the scientific basis for the promotion of energy-saving design of prefabricated shear wall residential building in the cold area.

Tianjin Shuangqing Home is located in the west of Beichen District of Tianjin, north side of Beichen West Road, its ground floor area reaches 128100m<sup>2</sup>. No. 8 building of Tianjin Shuangqing Home, built by Tianjin Housing Group, is the first fully prefabricated residential building of Tianjin. This paper takes the bedroom on the north side of the standard floor of No. 8 building as the research object, so as to reduce the influence of solar radiation on the heat transfer of the building envelope and improve the accuracy of the experimental results.

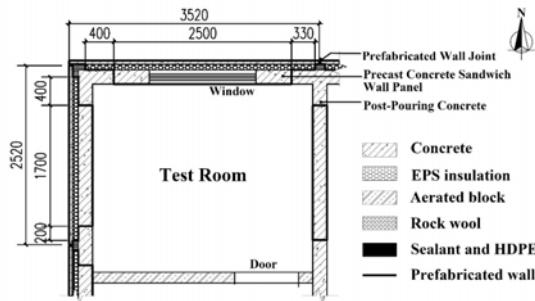


Figure 1. Plan of the test room and cross section of precast wall panel.

As shown in Figure 1, the main body of the construction is precast sandwich thermal insulation wall panel, the inner wythe and the outer wythe are concrete layers and the middle layer is the polystyrene board insulation, as shown in Figure 2. The joints between different precast wall panels are cast-in-place by concrete, called post-pouring concrete. There is rock wool filling between insulation layers, high density polyethylene(HDPE) bar and sealant sealing between outer wythes, to improve the overall tightness and insulation of the building envelope.

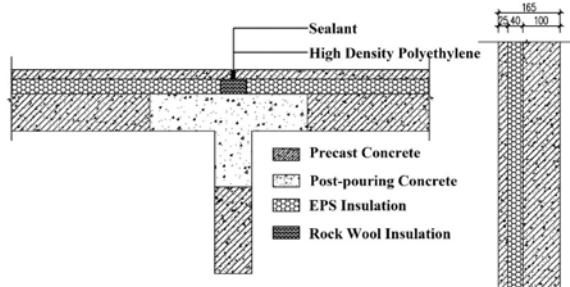


Figure 2. Cross section of precast wall panel.

The seam between post-pouring concrete and prefabricated wall panel, seam between prefabricated wall panels, thermal bridge are the parts that are easy to produce thermal defects. Therefore, using heat flow meter method to test the heat transfer performance of post-pouring concrete, precast wall panel and wall corner. Infrared thermal images of the inner and outer surface of the building envelope were obtained by using infrared thermography, to study thermal defections such as thermal bridges of seam between precast walls, reserved holes, construction.

## **The heat transfer performance of the building envelope**

### ***Heat flow meter method***

At present, the two main methods of building thermal performance test are hot box method and heat flow meter method. However, hot box method cannot be used to test the shaped thermal bridge. Therefore, the heat flow meter method is the most commonly used field test methods at home and abroad. The heat flow meter method uses heat flow meter and thermocouple measurement to record the heat flow and surface temperature to calculate the thermal resistance and heat transfer coefficient, to determine whether specific building satisfy energy conservation standards (Concepts, 2014).

In the test, heat flow meter is fixed on the measured construction and thermocouples are disposed inside and outside near the heat flow meter to record surface temperature. The test results are input to the data processing software in computer to calculate the thermal resistance and heat transfer coefficient.

In order to increase the temperature difference of the test room, enhance the accuracy of test results, two constant temperature heaters are disposed in the test room, the indoor temperature are stable at 25°C. The arrangement of heat flow meters and thermocouples is shown in Figure 3,4.

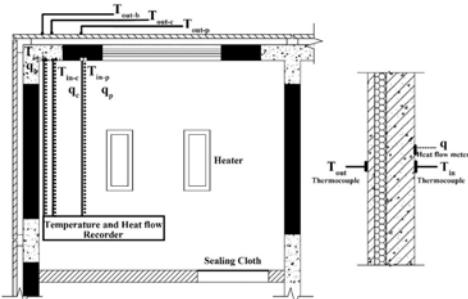


Figure 3. The layout of test equipment.



Figure 4. The photo of the test room.

Dispose the heat flow meters on the inner surface of wall corner, post-pouring concrete and precast wall panel to record the heat flow in the wall under the temperature difference between indoor and outdoor. These heat flow values are respectively marked as  $q_b$  (thermal bridge),  $q_c$  (cast concrete)  $q_p$  (precast wall panel). And close to the heat fluxes, thermocouple are fixed on the outside and inner wall surfaces to record the temperature fluctuation, respectively marked as  $T_{out-b}$ ,  $T_{in-b}$ ,  $T_{out-c}$ ,  $T_{in-c}$ ,  $T_{out-p}$ ,  $T_{in-p}$ . Moreover, the temperature and humidity recorder are fixed indoor and outdoor to record indoor and outdoor air temperature, named as  $Tr$ ,  $Te$  and calculate the average indoor and outdoor temperature, in order to calculate dew point temperature.

#### ***Calculation of heat transfer coefficient of the wall***

Through the collation of test data, we get the time varying curve of the indoor and outdoor surface temperature, as shown in Figure 5.

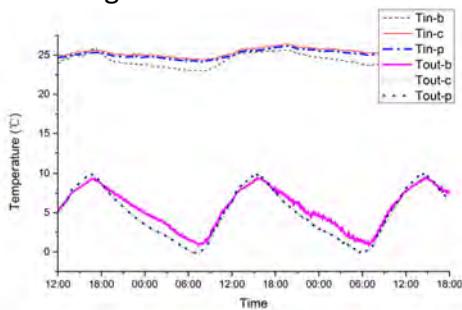


Figure 5. The time varying curve of the indoor and outdoor surface temperature.

Based on the principle of plate heat transfer, the heat transfer coefficient of the wall is calculated by the surface temperature difference and heat flux, we get that  $K_b$ ,  $K_c$ ,  $K_p$  is  $0.741 \text{ W}/(\text{m}^2 \cdot \text{K})$ ,  $0.607 \text{ W}/(\text{m}^2 \cdot \text{K})$ ,  $0.639 \text{ W}/(\text{m}^2 \cdot \text{K})$  respectively.

The results show that the heat transfer coefficient of the wall against post-pouring concrete and precast wall panel is consistent with theoretical value of  $0.6 \text{ W}/(\text{m}^2 \cdot \text{K})$ , proving satisfactory insulation performance. Moreover, it turns out that the heat transfer coefficient of wall against post-pouring concrete is slightly lower than that of the precast wall panel. Considering that the inner concrete wythe and insulation of precast sandwich wall are fixed together by factory prefabrication, with assurance of casting quality, the difference may attribute to that post-pouring concrete and precast wall insulation layer combine with each other with having certain air gap, which improves the insulation performance. Due to different heat transfer coefficients of two walls, thermal bridges need to be further studied by infrared thermography.

### ***Study on the condensation of thermal bridge between precast walls***

As shown in Figure 5, the temperature of inner wall surface in the corner between precast walls, is  $3^\circ\text{C}$  lower than that of precast wall and will produce more heat loss than wall.

Through the acquisition of hourly indoor and outdoor temperature, we get that average outdoor temperature is  $3.9^\circ\text{C}$  while average indoor temperature is  $25.8^\circ\text{C}$ , the average surface temperature of thermal bridge is  $22.6^\circ\text{C}$ . Based on definition of "Residential building energy efficiency inspection standards" (JGJ/T 132-2009), we calculate that the equivalent surface temperature of the thermal bridge under indoor and outdoor calculation temperature  $\theta I$  is  $13.9^\circ\text{C}$ , which is bigger than dew point temperature under 60% relative humidity,  $9.9^\circ\text{C}$ . Therefore, there won't be condensation in thermal bridge in the corner.

### **Detection of thermal defects using thermal infrared thermography**

#### ***Thermal defects of building envelope that may exist in prefabricated building***

Infrared thermography testing technology is a non-destructive testing technique to determine the surface temperature of the object. It is widely used in non-destructive testing of materials and structures, especially in the detection of building's thermal defects (Kylili et al, 2014). And the thermal defects of the building envelope are defects that affect the overall insulation performance, caused by improper construction and unreasonable design. Based on the characteristics of components' factory prefabricated production and field assembly of prefabricated building, we summary the thermal defects that may occur in prefabricated building, such as the thermal bridge of reserved hole in wallboard, seam between post-pouring concrete and precast wall panel, floor slab, seam between the walls and windows air infiltration.

#### ***Analysis of thermal defects of building envelope of prefabricated residential building***

##### ***Thermal bridge in reserved hole in wallboard***

In order to support the mould and fix the wall by casting, there is a need to design appropriate reserved hole, including bolt hole and grouting hole. The bolt hole and the steel support are connected by bolts to fix the precast wall panel. Besides, the bolt hole is also used to fix the casting mould when cast post-pouring concrete. What's more, another kind of reserved hole, grouting hole, is used for connection between precast sandwich wall and prefabricated steel bars of other walls. The base slurry flows through the grouting hole into grouting sleeve and after solidification, prefabricated wall and the prefabricated steel bars are fixed together (as shown in Figure 6). We can notice that if these reserved holes are handled improperly, there will be severe thermal bridge.



Figure 6. Bolt hole and grout hole.

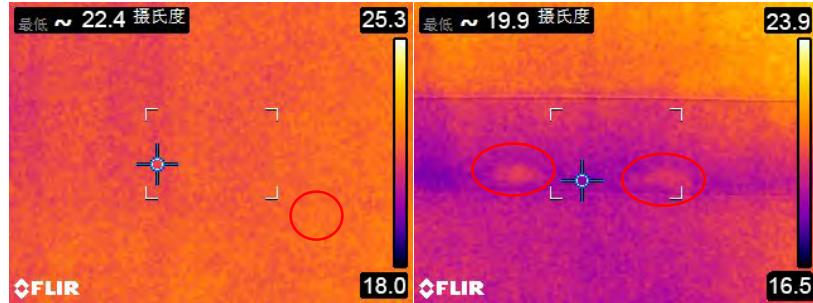


Figure 7. Infrared thermography of bolt hole and grout hole.

The infrared image shows that the temperature of inner surface of precast wall distributes uniformly, no thermal bridges exist in bolt hole and grouting hole. The phenomenon shows that there is no obvious difference between the thermal performance of the reserved hole and the main body of the wall, when the bolt hole and the grouting hole is filled with slurry. But there is facing layer hollowing on the baseboard, which may lead to finishes off and influence insulation performance. The phenomenon is due to improper construction, so the construction quality must be guaranteed.

#### *Thermal bridge in seam between post-pouring concrete and precast wall panel*

Seams between post-pouring concrete and precast wall panel are also potential thermal defect. The post-pouring concrete is cast-in-place to connect with the precast sandwich wall while precast wall panel is produced by factory integration casting.

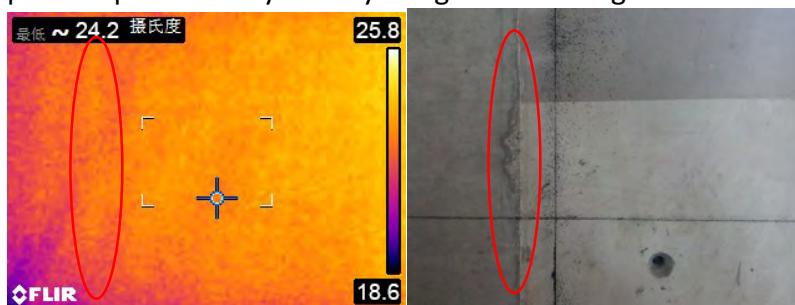


Figure 8. Infrared thermography of the seam between post-pouring concrete and precast wall panel.

As shown in Figure 8, the left side is post-pouring concrete while the right side is precast wall panel. The temperature distribution of the inner surface of the precast wall panel is pretty uniform, better than that of the post-pouring concrete. In addition, the seam is obvious in the image and there is a temperature difference of 1°C between two parts. It indicates that there is difference in insulation performance and slight thermal bridge.

To reduce the effect of the defect, in the design stage, appropriate solutions should be adapted to reduce the difference in insulation performance.

#### *Thermal bridge in seam between precast wall panels*

The seam between precast wall panels is also a kind of possible thermal defect, whose heat transfer and sealing performance have an important impact on the overall heat transfer and

sealing performance of the building envelope. In the vertical and horizontal direction, the seam between precast wall panels are filled with high density polyethylene(HDPE) bar and sealed by sealant.

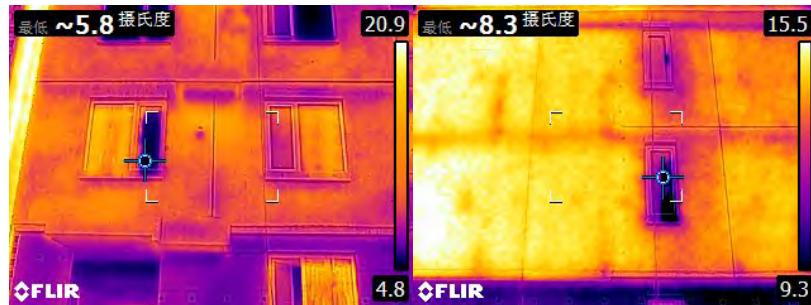


Figure 9. Outdoor infrared thermography.

As shown in Figure 9, the black line is the seam between precast wall panels, whose temperature distribution is almost identical with the precast wall. It turns out that seam between precast wall with HDPE bars filling and sealant sealing has the same heat transfer performance as the wall and there are no thermal defects existing.

#### *Thermal bridge in the wall corner*

The outer wythe and EPS insulation of transverse and longitudinal walls are connected with each other with rock wools filling between insulations and HDPE bars filling and sealant sealing between outer wythes. The sealing quality and the tightness are the key factors to thermal bridges in the corner.

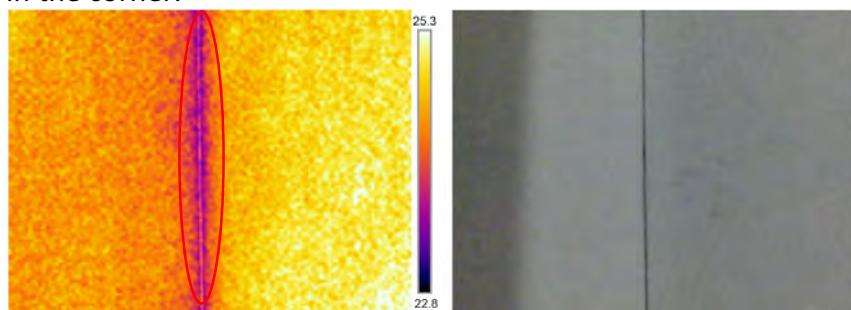


Figure 10. Infrared thermography of thermal bridge in the corner.

The photo shows that thermal bridges of prefabricated residential building are similar to that of the cast-in-place concrete building, in the defect area and defect level, showing that thermal bridges of prefabricated residential building don't get worse because of its complex structure layer with appropriate insulation treatment.

#### *Thermal bridge in the floor slab*

The construction of composite floor slab is shown in Figure 11, 300mm precast floor slab is fixed on the precast wall panel with 300mm concrete pouring on. The end of the floor slab is closed by the EPS insulation to satisfy the insulation requirement.

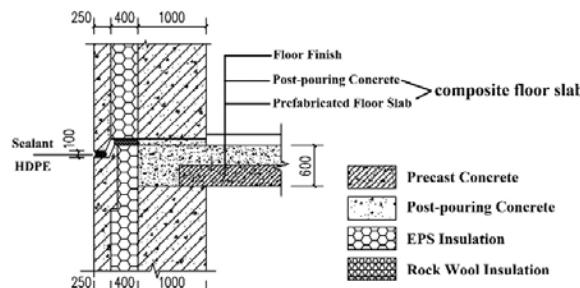


Figure 11. The construction of composite floor slab.

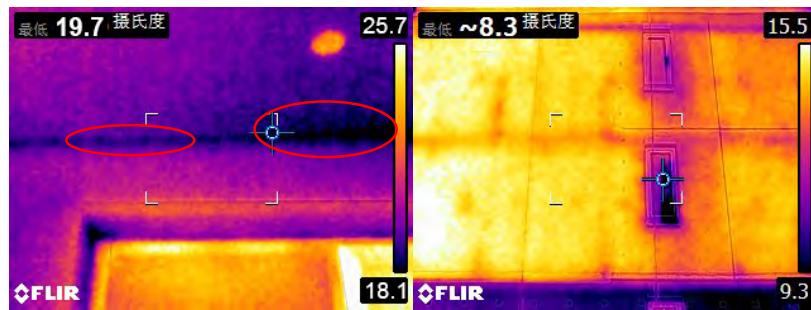


Figure 12. Infrared thermography of thermal bridge in the floor slab.

The infrared thermography shows that the thermal bridge in the floor slab is pretty obvious and heat transfer is centralized. It is because the heat flux through the joint between wall and floor is obvious but insulation layer is thinner, which aggravates the thermal bridge in the floor slab. What's worse, the defect area is not uniform where some places have more centralized and obvious heat flux. Many factors such as pouring quality, match between walls and precast floor slab will lead to the phenomenon.

Therefore, to further strengthen the connection and insulation between wall and floor slab, reduce the thermal bridge in the floor slab needs to be taken into consideration in the design, such as the optimization of wall-floor connection, enhance the floor wall insulation performance, etc.

#### *Window air infiltration*

Buried wood blocks are prefabricated along the window opening to be used for fixing the window. After the structure's completing, the window and wood blocks are connected by expansion bolt and the gap is sealed by sealant. Therefore, the connection may have obvious air infiltration if window and wall doesn't match precisely or sealant isn't filled well.

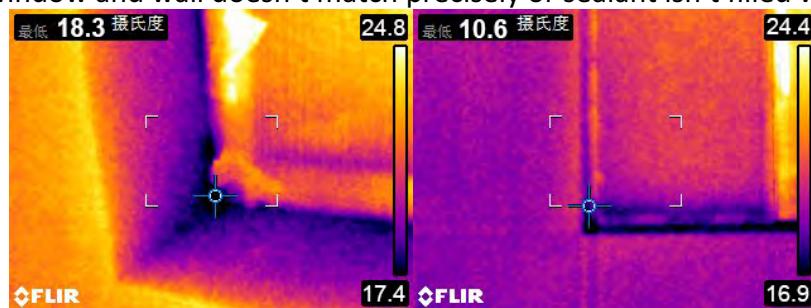


Figure 13. Infrared thermography of the window.

The infrared image displays that temperature around window is obviously lower than that of the wall, showing that there is obvious air infiltration and heat loss is huge. Therefore, the window air infiltration another obvious and severe thermal defect. Designers should change the simple connection method between window and wall or enhance the seal method to improve the air tightness and reduce the heat loss by air infiltration.

#### **Conclusions**

Through the heat flow meter and the infrared thermal imager, the possible thermal defects of the prefabricated shear wall residential building in cold area are studied. We can get the following conclusions.

There is a difference in heat transfer for post-pouring concrete and precast wall panel and it leads to the slight thermal bridge. The connection method needs to be improved;

There is no condensation in the corner based on the fact that the equivalent surface temperature of thermal bridge is higher than calculated condensation temperature. The temperature distribution of the inner surface of the precast wall is uniform while that of post-pouring concrete is uneven with local heat flow obvious.

After the appropriate insulation and sealing treatment, there is no obvious thermal bridges caused by reserved holes, which has the identical insulation performance with the wall. Thermal bridges of prefabricated residential building don't get worse because of more complex constructions. They are similar to that of the cast-in-place concrete building in the defect area and level.

The insulation thickness between precast wall and floor slab is unreasonable, which leads to obvious and severe thermal bridge. Designers should focus on the optimization of connection and enhance the insulation performance. There is obvious cold air infiltration at the joint between the window and the wall. The joint should be optimized to improve the sealing and reduce the heat loss.

There are many potential thermal defects for prefabricated residential building because of its complex material structure and assembly methods. However, the results show that these thermal defects can be reduced or even eliminated with appropriate heat treatment. And there are still many obvious thermal defects like severe thermal bridge in floor slab because of unreasonable design, obvious windows air infiltration, slight thermal bridge in the seam between post-pouring concrete and precast wall panel and facing layer hollowing.

The paper points out the existing thermal defects of the prefabricated shear wall building in cold area using heat flux method and infrared thermography, in order to provide the scientific basis for improvement of insulation performance of building envelope and promote further development of the prefabricated residential building in cold area.

## References

- Jaillon, L., Poon, C. S. (2009). The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Automation in Construction*, 18(3), 239-248.
- Zhao, Q., Zhang, Z., Qiu, G., Liu, J. and Chu, M. (2014). Experimental Study on Mechanical Behaviors of Precast Concrete Shear Wall with Vertical Joint. *Applied Mechanics and Materials*, 584-586, pp.1299-1303.
- Yooprasertchai, E., Hadiwijaya, I. and Warnitchai, P. (2016). Seismic performance of precast concrete rocking walls with buckling restrained braces. *Magazine of Concrete Research*, 68(9), pp.462-476.
- Concepts, R. (2014). Standard practice for in-situ measurement of heat flux and temperature on building envelope components. *International Journal of Pharmacology*, 7(8), 836-842.
- Kylili, A., Fokaides, P. A., Christou, P., Kalogirou, S. A. (2014). Infrared thermography (IRT) applications for building diagnostics: A review. *Applied Energy*, 134, 531-549.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Identifying cost trend and affected cost factors for green office buildings in Australia

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**Abstract:** The integration of sustainability and sustainable practices in the construction industry is ultimately benefitting the environment, society, and economics. Many green office buildings in Australia achieved Green Star ratings have claimed outstanding achievements such as energy efficiency, greenhouse gas reduction, healthy work environment, and productivity growth. However, in deciding to develop office projects, one of the main barriers identified is the additional cost that varies across Australia and globally. This creates a dilemma for making decisions to develop green buildings, particularly for those who follow the business as a usual approach. Utilising secondary data published through the literature, including grey literature, the paper aims to show the cost trend for green office buildings in Australia and to identify affected-cost factors. The literature draws upon relevant information of cost, green features and Green Star ratings in office projects. The information is based on experts' studies published in standard academic sources and other sources, such as Green Building Council of Australia (GBCA) and peak industry bodies. The twelve-year worth of data and the information of 187 projects are examined. This paper will form the foundation for further research and for the encouragement of stakeholders to promote sustainable development in the construction industry.

**Keywords:** cost trend, Green Star, green office buildings, green features, Australia.

### Introduction

Our global environment has been impacted by the construction industry through its greenhouse gas emissions, resources consumption and waste (Zhao et al., 2011). The construction industry accounts for 40 per cent consumption of world's resources, 40 per cent of global energy requirements, about 30 per cent of greenhouse gas emissions and 25 per cent of water usage (UNEP, 2016). The highly negative impact leads the construction industry to move to sustainability for achieving the win-win solution through the balance of the improved environment, economic prosperity and social justice (Elkington, 1997).

Sustainability has received greater traction in the Australian construction industry about twelve years. It has evolved significantly from the year of 2003 largely due to the establishment of GBCA: the Green Building Council of Australia. The benefits of green buildings or buildings meeting sustainability are generally to improve users' health, safety, productivity, and to reduce absenteeism (Ries et al., 2006, Kats et al., 2003). It also increases property market value (Yudelson, 2010), saves operational cost (Vatalis et al., 2011, Liu et al., 2014, Gabay et al., 2014, Ries et al., 2006), and reduces greenhouse gas emissions, energy and water consumption, materials use, and wastes (Kats et al., 2003).

Following these advantages, green buildings have been integrated into office projects, which account for the major proportion of the construction industry in Australia. Indeed, the stock of office buildings is about 42.06 million m<sup>2</sup> of gross floor area in 2016 and expected to grow to 45,7 million m<sup>2</sup> of gross floor area in the year of 2020 (DCCEE, 2017). The total energy consumption is about 39.7 PJ and the greenhouse gas emission is 10.3 Mt CO<sub>2</sub>-e in 2011, accounting for 1.8 per cent of national greenhouse gas emissions (DCCEE, 2017). It can be said that the office building sector is one of the biggest energy consumers and greenhouse gas emitters. The office building sector is also identified as one of nine main sectors contributing towards a sustainable future (Zuo et al., 2016). It is, therefore, a critical need for promoting the sustainable principles into office building design that will reduce their environmental impacts and to develop sustainable future.

However, generating these achievable benefits may require the additional cost, which is one of the key barriers for adopting sustainable development principles into office building projects. The additional cost for green projects has been mentioned in many previous studies (Issa et al., 2010, Hwang and Tan, 2012, Yudelson, 2010, Kim et al., 2014) and has been concluded inconsistently and arguably. On the one hand, Matthiessen et al. (2007) and Rehm and Ade (2013) noted that no additional cost was incurred to achieve LEED Certification in US and Green Star certification in New Zealand. On the other hand, there was a wide range of the additional cost for LEED certifications from 2 per cent of construction cost (Kats et al., 2003) to 13.8 per cent of the cost (Kats, 2010). In Australia, the study by Langdon (2007) also showed that 3-5 per cent of the additional cost was for 5-Star, and 5 per cent was for 6-Star buildings without iconic design in green office projects. Additionally, the research by Bond University showed that there was no significant additional cost for Green Star Certification process (GBCA, 2008). These various findings of the cost can be the barrier to making the decisions toward sustainability in office projects.

Although sustainability has been developing as the mainstream in the construction industry, the cost is still a primary barrier to hamper the development of green office buildings in Australia. This barrier can be broken by the examination of the cost reduction or the downward cost trend and the identification of the affected-cost factors during the twelve years in Australia. The cost trend and the factors may change the stakeholders' perceptions about the cost, and then encourage them to promote the integration of sustainability into the construction industry in this country.

The paper begins with the introduction of the green rating tools in Australia. This is followed by the analysis of green features, green technologies, and the cost in order to identify the cost trend during the twelve years since the introduction of Green Star in the marketplace and to explore cost-affected factors. The paper forms the foundation for further research as well as provides a reference for stakeholders in their decision-making of sustainable office projects.

## **Research scope**

A sustainable building is also known as a green building in Australia and globally so the words of sustainability and green in this paper are used interchangeably. The green building concepts have been developed in Australia through the governmental policies of the green encouragement and the establishment of Green Building Council of Australia (GBCA) at the end of 2002. Broader market involvement and consumer engagement in the green building movement in Australia firstly started in 2000 Sydney Olympic Games known as the "Green Games", and the approach towards green buildings has strongly influenced the

marketplace. Green Star rating tool was launched in 2004 and is the “second-generation rating tool” that has been adopted in Australian context based on LEED (US) and BREEAM (UK). This tool development and its market engagement have been managed by GBCA, a non-profit organization to assist the development of sustainability in Australia. The Green Star tool has been transformed continuously to meet the requirements of green projects in this country and around the world.

For Green Star - Office Design, there are three levels of Green Star Certification, namely 4-Star, 5-Star, and 6-Star. The level is dependent on the points that a project gains in the green assessment. 4-Star is 45-59 points and indicates as “Best Practice”. 5-Star is from 60 to 74 points and is known as “Australian Excellence”. Lastly, 6-Star is 75-100 points, awarding “World Leader”. The points can be gained from eight main categories of Management, Indoor Environment Quality (IEQ), Energy, Transport, Water, Materials, Land Use and Ecology, and Emissions. In addition, Innovation is the ninth category to add extra points to a project (Dadzie et al., 2017).

In this paper, 47 green features are selected to analyse based on the review of the GBCA report and previous studies of Green Star-rated buildings. Actually, green features are not required specifically in the Green Star ratings. Green features that have been adopted by the construction industry to achieve the green points are often under different Green Star categories, including Innovation category in the early days of this tool rollout. GBCA (2008) developed a matrix of 70 green features from low to high sustainable technologies as well as the cost associated with these features. In addition, 22 green features implemented in office buildings were explored by another study conducted in Australia (Dadzie et al., 2017). Zuo et al. (2016) also found 21 and 16 green features for easier and more difficult for awarding Green Star, respectively. This research was the analysis of green features that are easier or more difficult to obtain in every category of Green Star – Office Design and Green Star – As Built. From these studies, green features are numerous and depend on the development of green technologies and green practices. After examining green features' information of 187 projects (from GBCA website and websites of peak industry organizations involved in green projects) and comparing with the list of green features of these above studies, the paper shortlisted 47 common green features in most research.

Besides that, among 356 Green Star-rated office projects from 4-Star to 6-Star in three Green Star – Office Design versions (v1, v2, and v3), 187 projects are selected and coded from P1 to P187, accounted for 53 per cent of total Green Star-certified projects. The projects are nominated by the criteria of a new-build project.

## **Methodology**

The findings of this paper are mainly based on the secondary data analysis. This method utilises the existing data by collecting, compiling, and archiving information to draw out research outcomes (Vartanian, 2010). This method takes the advantage of data availability, especially the longitudinal and cross-sectional data. However, the data needs to be checked for reliable, suitable, and adequate reasons. In the case of this research, the secondary analysis will assist to identify the cost trend and affected-cost factors relied upon available data. This method is to re-analyse the existing data to identify the findings of research (Smith and Smith Jr, 2008).

The secondary data is collected from GBCA websites mainly, especially GBCA directory and case studies. It is also gathered from other sources like published studies and grey data

as well as websites of stakeholders related to projects. The collected data is mainly about the project information, green features, green technologies and cost information.

## Analysis and Findings

### ***Green Star – Office Design in Australia***

Of the 356 projects as mentioned above, 187 projects are analysed in this paper. These projects are from eight states and territories in Australia, namely Victoria (VIC), Queensland (QLD), New South Wales (NSW), Western Australia (WA), Australian Capital Territory (ACT), South Australia (SA), Tasmania (TAS), and Northern Territory (NT). Based on Figure 1, large numbers of certified projects are in VIC, QLD, and NSW and accounted for 69 per cent of total certified projects in Australia. There are 51, 50 and 28 projects for each state, respectively.

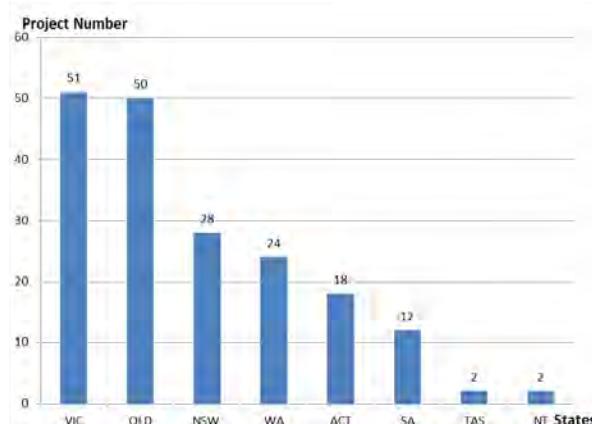


Figure 1. Certified buildings - office design for new build projects in Australian States and Territories

The numbers of certified projects are different in every version of Green Star – Office Design. The majority of projects are in the version 2, especially 4-Star and 5-Star ratings, making up 63 per cent of total projects (see Figure 2). The next larger project number is 45 projects certified 5-Star – Office Design version 3 (taking up 24 per cent). From version 1 to version 2, the number of projects surges dramatically by about 15 times, from 8 projects to 117 projects for version 1 and version 2, respectively. The increase of certified project numbers presents the significant green movement toward office buildings in Australia, especially during the time of 2006 to 2014.

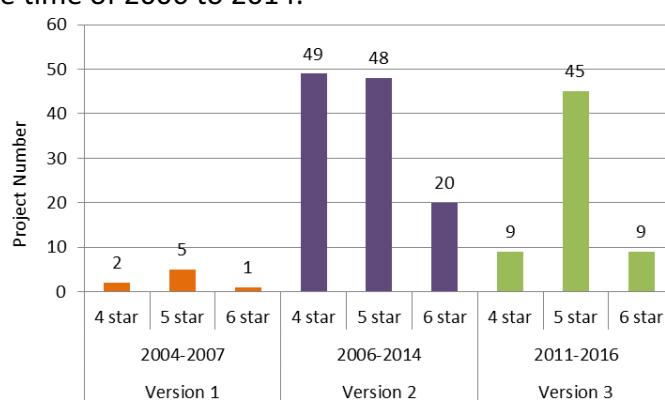


Figure 2. Certified office buildings within different versions and Green Star

### ***Green features, green technologies, and green star rating***

As indicated above, 47 green features are coded for the reason of data analysis as below:

Table 1. The code table of 47 green features

Code	Green Feature	Code	Green Feature
GF1	Reuse of existing building site	GF25	Dedicated tenant exhaust riser
GF2	Detailed building users' guide	GF26	Zero ODP refrigerants
GF3	Removal of cooling towers from design	GF27	Construction waste recycling
GF4	Cooling tower water treatment	GF28	PVC minimization in materials
GF5	Water efficient cooling tower	GF29	Bicycle storage, change rooms, showers
GF6	Rainwater storage and use	GF30	Percentage of NLA with external views
GF7	Constructed wetland storm-water filter/treatment	GF31	Subsoil landscape irrigation
GF8	Dedicated recycling waste storage area	GF32	Small car parking spaces (based on NABERS)
GF9	Interactive BMS	GF33	Carbon Dioxide Monitoring and Control
GF10	Sub-metering is to be installed for all substantive base building uses	GF34	Glare reduction by blinds and/or shading
GF11	Sub-metering is specified for all tenancies within the building	GF35	Low VOC paints, stains, adhesives, sealants, and carpets.
GF12	High induction supply swirl diffusers	GF36	Wind turbine
GF13	External shading devices	GF37	Photovoltaic system
GF14	Reduction in photocopiers/ printers due to dedicated rooms	GF38	Low e-double glazing
GF15	T5 fluorescent lighting	GF39	Trigeneration technology
GF16	Zero ODP building thermal insulation	GF40	A roof mounted tri-generation plant
GF17	Water meters linked to BMS for leak detection	GF41	Gas-fired tri-generation plant
GF18	Certified or recycled timber	GF42	Gas-fired cogeneration plant
GF19	Water efficient fixtures and fittings	GF43	Chilled beam system
GF20	High frequency ballast	GF44	Daylight sensor lighting
GF21	Environmental Management Plan	GF45	Internal atrium
GF22	Increase outside air rates by 50 per cent above AS 1668.2-1991	GF46	Greywater treatment system
GF23	Efficient lighting design and zoning	GF47	Rain water harvesting
GF24	Structural steel with $\geq$ 50 per cent postconsumer recycled content		

According to Figure 3, the collected database enables to explore these green features that were attributed mostly in the categories of Management and IEQ such as GF21 (181 projects), GF20 (173 projects), GF2 (165 projects) and GF23 (165 projects). The green features, that are hard to achieve, are in the categories of Energy and Water such as GF40 (1 project), GF41 (2 projects), GF38 (6 projects), and GF5 (2 projects).

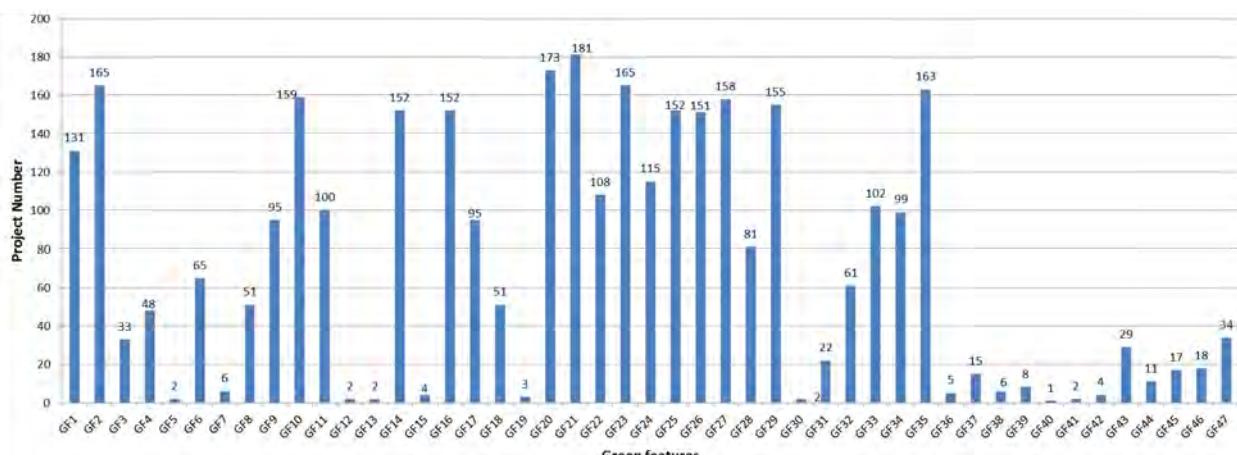


Figure 3. 47 green features in 187 certified projects

Figure 3 also shows that the number of green office projects designed with green features in categories of Energy and Water is smaller than the number of green features in other categories. Although there is the encouragement for implementing high technologies as the photovoltaic system (GF37) and wind turbines (GF36), there are only 15 projects and 5 projects used in their designs, respectively. More specially, the high technologies are often applied in the 6 star – rated office projects. It can be concluded that Management is awarded by most of the projects while Energy and Water categories are harder to achieve green credits.

### ***Cost trend for three versions of Green Star- Office Design***

The cost information is collected through websites of GBCA, developers, main contractors, and consultants involved in projects. As the cost information of green office projects is limited in Australia, there is only the collection of cost data for 102 certified projects, taking up 55 per cent of total projects. The cost is evaluated at the cost per square meter to explore the cost changes in different Green Star ratings – Office Design versions and time duration.

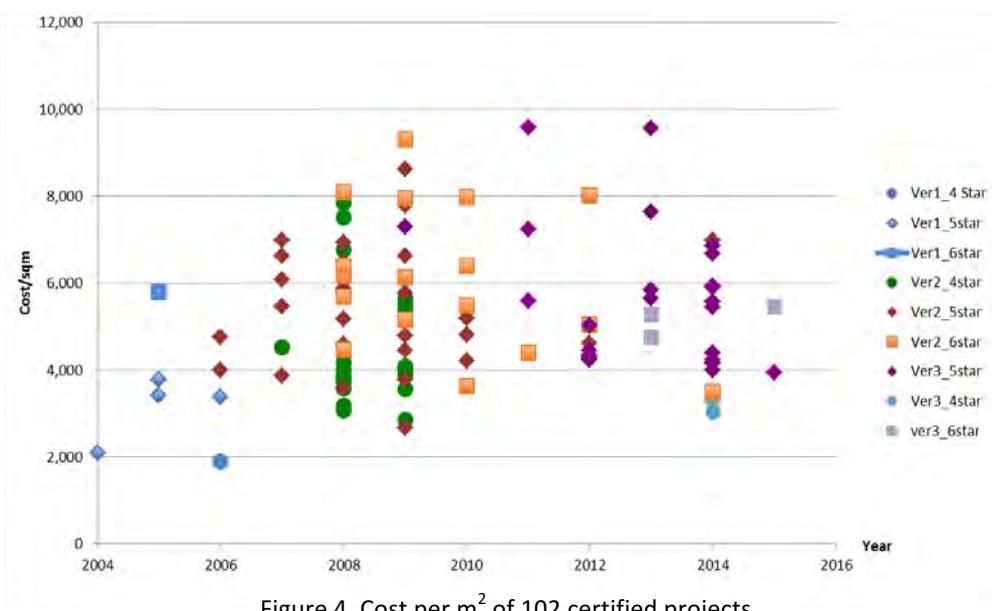


Figure 4. Cost per  $\text{m}^2$  of 102 certified projects

Figure 4 shows the pattern of the downward cost trend in the same Green Star of different versions. In other words, the costs for achieving 4-Star, 5-Star, and 6-Star have been reduced from version 1 to version 3, especially for 5-Star and 6-Star. In the initial stage of green development, the cost increased significantly between 2004 and 2010. After that, the cost trend descended slowly, excepting the cost of iconic projects as the expectation of developers and investors. P8, as an example, was the iconic project in 2005 with the use of many high green technologies such as wind turbine, automatic night-purge windows, co-generation, chilled beams, and photovoltaic system. The cost for these green features was 11.30 million and the cost gap was 22 per cent (Stewart et al., 2012). These features caused the dramatic increase in building cost. Therefore, the green ratings, green technologies, and green features impacted the cost significantly, especially in the first building generation.

### **Discussions and conclusions**

There are many significantly important findings for the development of green office buildings in Australia. The paper presents the downward trend of the cost for Green Star-

rated projects during twelve years. In addition, the paper identifies the factors that impact the cost. These findings are worthy for the further research as well as the reference for those who aim to integrate sustainable development principles into their projects.

Firstly, there was a dramatic increase of green building number during 2006-2014. This increase could be from the integration of sustainability into building code of Australia to support the construction of green office buildings (BCA, 2003). Additionally, many different policies and programs introduced in various states were used to encourage the green development. From the government perspective, policies drove sustainability outcomes in the marketplace such as Queensland Government Sustainable Planning Act 2009, Greener Government Buildings Program (GGB) in Victoria and Victoria Energy Efficient Target (VEET). From the private sector, financial institutions had many green loan products or programs to demonstrate their commitment to environment and community such as Generation Green™ of Bendigo and Adelaide Bank, NAB Environmental Upgrade Funding. Another reason that green building number increased significantly is the new green practices that were launched in 2009. By that time, manufacturers and suppliers were able to keep with green building trends and had a chance of new green marketplace from GBCA and produced new green products (GBCA, 2010). These products assisted the cost reduction by providing sustainable alternatives. It is comprehended that the appearance of new green products, the integration of sustainability into BCA, policies from states, government, and programs from financial institutions have impacted noticeably the cost of green building and the green movement in the construction industry.

Secondly, there are the different levels of the additional cost to award Green Star Certification. Project P109 is a good example as a case-study from GBCA (GBCA, 2013). This project used wind turbines (GF36) as the green technology in the design but it was not installed during construction time. Actually, wind turbines were selected for their visual demonstration of environment commitment. However, due to the specific public concerns, financial risks, and technology barriers halted the installation of these wind turbines (GBCA, 2013). It seems that green office projects are affected by cost and other issues such as community concerns and green technologies.

Thirdly, the cost trend of Green Star-rated projects is in general downward trend during twelve years. It means that the cost of the first generation is often higher than the cost of the later generation. The reasons of this reduction can be the alternatives of green technologies, the effectiveness of the green features selection and the cost reduction of materials. Alongside the time, the alternatives can reduce the cost significantly such as the cost trend of solar panels technology from 2004 to now. Green Star Certification is, therefore, possibly awarded with neutral cost or additional cost depending heavily on green features and green technologies selected.

In conclusion, the cost for obtaining Green Star Certification reduces as it is shown by the analysis of the cost trend during twelve years. An office project can get Green Star with or without additional cost if there are the efficient selection of green features and the effective management of affected-cost factors. Based on this research, the cost of green buildings can be impacted by the factors of government policies and private programs, green technologies, green products, construction time, project location, project procurement, culture and community involvement. These affected-cost factors will be examined further in the next research step to explore reasons for the downward trend of cost in green office projects in Australia.

## References

- BCA. (2003). *Sustainability and the Building Code of Australia* [Online]. Available: [http://www.vba.vic.gov.au/\\_data/assets/pdf\\_file/0007/19582/Sustainability-and-the-Building-Code-of-Australia.pdf](http://www.vba.vic.gov.au/_data/assets/pdf_file/0007/19582/Sustainability-and-the-Building-Code-of-Australia.pdf) 2017].
- DCCEE, Department of Climate Change and Energy Efficiency (2017). *CBBS Model - Office Buildings* [Online]. Available: <http://www.environment.gov.au/energy/energy-efficiency/non-residential-buildings/cbbs-model-office-buildings> 2017].
- Elkington, J. (1997). Cannibals with Forks. *The triple bottom line of 21st century*.
- Gabay, H., Meir, I. A., Schwartz, M. & Werzberger, E. (2014). Cost-Benefit Analysis of Green Buildings: An Israeli Office Buildings Case Study. *Energy and Buildings*, 76, pp.558-564.
- GBCA. (2008). *The Dollars and Sense of Green Buildings : Building the Business Case for Green Commercial Buildings in Australia*, Sydney, N.S.W., Green Building Council of Australia.
- GBCA. (2010). *A Decade of Green Building 2002-2012* [Online]. Available: <https://www.gbc.org.au/uploads/170/34474/A%20decade%20of%20green%20building.pdf> 2017].
- GBCA. (2013). *2 Victoria Avenue, Perth* [Online]. Australia: GBCA. Available: <https://www.gbc.org.au/green-star/green-building-case-studies/2-victoria-avenue-perth/> [Accessed 06/03/2017 2017].
- Hwang, B.-G. & Tan, J. S. (2012). Green Building Project Management: Obstacles and Solutions for Sustainable Development. *Sustainable Development*, 20, pp.335-349.
- Issa, M. H., Rankin, J. H. & Christian, A. J. (2010). Canadian Practitioners' Perception of Research Work Investigating the Cost Premiums, Long-Term Costs and Health and Productivity Benefits of Green Buildings. *Building and Environment*, 45, pp.1698-1711.
- Kats, G. (2010). *Greening Our Built World: Costs, Benefits, and Strategies*, Island Press.
- Kats, G., Alevantis, L. & Capital, E. (2003). *The Costs and Financial Benefits of Green Buildings: A Report to California's Sustainable Building Task Force*, Capital E.
- Kim, J.-L., Greene, M. & Kim, S. (2014). Cost Comparative Analysis of a New Green Building Code for Residential Project Development. *Journal of Construction Engineering and Management*, 140, pp.05014002.
- Langdon, D. (2007). The Cost and Benefit of Achieving Green Buildings. *Second Quarter*. Retrieved August, 2, pp.2012.
- Liu, Y., Guo, X. & Hu, F. (2014). Cost-Benefit Analysis on Green Building Energy Efficiency Technology Application: A Case in China. *Energy and Buildings*, 82, pp.37-46.
- Matthiessen, L. F., Morris, P., Langdon, D. & Association, C. A. B. (2007). *Cost of Green Revisited: Reexamining the Feasibility and Cost Impact of Sustainable Design in the Light of Increased Market Adoption*, Continental Automated Buildings Association.
- Rehm, M. & Ade, R. (2013). Construction Costs Comparison between 'Green' and Conventional Office Buildings. *Building Research & Information*, 41, pp.198-208.
- Ries, R., Bilec, M. M., Gokhan, N. M. & Needy, K. L. (2006). The Economic Benefits of Green Buildings: A Comprehensive Case Study. *The Engineering Economist*, 51, pp.259-295.
- Smith, E. & Smith Jr, J. (2008). *Using Secondary Data in Educational and Social Research*, McGraw-Hill Education (UK).
- Stewart, P., Robinson, J. & Low, S. (2012). The Business Case for Sustainable Design-the City of Melbourne Ch2 Project. *Construction Economics and Building*, 5, pp.58-70.
- UNEP. (2016). *Why Buildings* [Online]. Available: <http://www.unep.org/sbci/AboutSBCI/Background.asp> [Accessed January 09 2016].
- Vartanian, T. P. (2010). *Secondary Data Analysis*, Oxford University Press.
- Vatalis, K. I., Manoliadis, O. G. & Charalampides, G. (2011). Assessment of the Economic Benefits from Sustainable Construction in Greece. *International Journal of Sustainable Development & World Ecology*, 18, pp.377-383.
- Yudelson, J. (2010). *The Green Building Revolution*, Island Press.
- Zhao, L., Guo, Y. & Lu, N. The Greenhouse Gas Emission Factors Study in Construction Industry. Water Resource and Environmental Protection (ISWREP), 2011 International Symposium on, 20-22 May 2011 2011. pp.2381-2384.
- Zuo, J., Xia, B., Chen, Q., Pullen, S. & Skitmore, M. (2016). Green Building Rating for Office Buildings - Lessons Learned. *Journal of Green Building*, 11, pp.131-146.



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*Design to Thrive*

## Comparison of Japanese and British off-site housing manufacturers and its relation with low/zero energy/carbon houses

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**Abstract:** This study has the objective to compare how Mass Customisation processes have been utilised to deliver sustainable housing in Japan and the United Kingdom (UK). Nowadays, Japanese manufacturers have to lead the mass prefabrication of dwellings that accompanied with strict local environmental policies, are capable of delivering zero-energy houses in marketable prices, and aim to introduce zero-carbon models in coming years. Their high-quality production systems are a consequence of decades of self-improvement and constant sales. On the other side, the UK government and industry advisors have stressed the necessity of increasing the use of off-site/modern methods of construction, not only to fulfil the housing shortage but as a solution to the energy performance issues. Therefore, this study presents a comparison between both contexts based on visits to housing factories. The information gathered on the visits was complemented with related literature and economic and socio-political quantitative data. The objective of this paper is to highlight the differences and similarities of both practices to identify the barriers that the introduction of the Japanese practice could have in the UK; which open the discourse of implementing Mass Customisation strategies to achieve higher energy efficiency and to promote the use of renewables.

**Keywords:** Housing, Mass Customisation, Zero Energy/Carbon, Japan vs. UK, Off-site construction.

### Introduction

What are the choices available to house buyers in the UK? As you survey the new build market, you find that houses are sold by room count and location. If the buyer wishes to acquire a low carbon dwelling, then the choice afforded by the open market is extremely limited. In these cases, those with time, money and persistence will employ an architect for what is essentially a bespoke service. Procuring a building in this way is more expensive and time-consuming (Shafik and Martin, 2006). The benefits of standardisation regarding quality as defined as consistency, price certainty and production efficiencies are lost.

The Japanese experience is quite different. Essentially because the UK market is driven by land price. The return for the housing companies come from maximising the value of developed land, or what is known as 'land banking' (Johnson, 2007: 31-32). The design and production of buildings is commodified, and the asset base of large housing suppliers rarely includes construction capacity which is in reality subcontracted out to smaller companies often only carrying single trades. In Japan, a return on investment for housebuilders comes primarily from the design, manufacture and sale of off-site dwellings. Over 90% of the new

constructed houses are detached<sup>1</sup>, where three-quarters of them are built on the own customer plot of land (Barlow and Ozaki, 2005: 11; Barlow *et al.*, 2003: 137—Management and Coordination Agency, 1996). Over time, this has meant that an emphasis on efficiency and quality has ensured the sector to be dominated by operators with a background in engineering manufacture, other sectors or conceived as extensions of existing conglomerates (Duncan, 1973: 62; Johnson, 2007: 20; Gann, 1996: 443<sup>2</sup>).

Although, ostensibly about mass production, increasing sophistication in inventory management, automation and marketing has led to the appearance of greater choice and agency by the customer through a process known as 'mass customisation' — a phenomenon that mirrors similar developments such as in the automobile sector (Barlow, 1999: 30; Gann, 1996: 447).

With such an approach comes many of the benefits rarely seen in UK housebuilding, high levels of quality control through off-site manufacture and critically an opportunity to choose a level of specification limited only by cost. Although the customer is empowered, in reality, it is predicated on a circumscribed number of variants to a base design. All of these variants, however, can be tested and simulated to allow clear guidance to consumers as to the energy costs and carbon impacts of their building both in terms of embodied and operational energy, which allows consumers to make informed choices helped by sophisticated tools and visuals (Noguchi, 2005: 28), which offers the purchasers a *soft path* to opt for a low carbon product at any point in the sales process. In the UK a housebuyer very often has to commit, almost as an *article-of-faith*, to a zero carbon solution from the very beginning of the procurement process. In contrast, in Japan the informed choices made by the housebuyer contribute to a *take-up* of zero energy/carbon dwellings.

Mass customisation appears as the key strategy used by Japanese housing manufacturers to increase the quality and efficiency of their products by adjusting their production processes<sup>3</sup> to the customer's wants and financial capacity. As the plots are already owned by the customer, housebuilders use mass custom strategies to differentiate themselves and compete (Barlow and Ozaki, 2005: 18). Therefore, this study aims to compare these processes in both contexts to identify possible crossovers that could be applied in the UK to increase the delivery of energy efficient dwellings. Moreover, the study does not pretend to suggest solutions, rather open a discourse on which and how the observed processes could be applied in a beneficial manner.

### **Summary of the evolution of Japanese and British Housing industry**

During the 1940s and 1950s, the first prefabricated house models were marketed in Japan. Examples of this era: the Junzo Sakakura and Kiyoshi Ikebe constructions systems that utilise industrialised elements and Maekawa's 'Prefabricated Maekawa Ono San'in Manufacturing' (PREMOS)<sup>4</sup>, which produce more than 1,000 units in total (Bergdoll and Christensen, 2008: 33; [prefabricate.blogspot](#), 2016). In the UK, prefabricated projects can be spotted from

<sup>1</sup> Ritsuko Ozaki and John Rees Lewis (2006: 100) state that detached houses are the main form of housing; physical proximity to the neighbours would threaten the safety. They are referencing this statement with Hall's text of 1966: 'The Hidden Dimension'.

<sup>2</sup> David M. Gann described Japanese industries venturing into the housing sector as the '*demand for construction work to repair war-damaged housing and improve the general quality..., triggering a need to modernize construction processes...*'.

<sup>3</sup> William Johnson (2007: 38) state that build quality in ***prefabrication relates to a process not a product***, citing A Craig, R Laing and M Edge's 2000 conference proceeding publication called 'The social acceptability of prefabrication and standardisation in relation to new housing'.

<sup>4</sup> Kunio Maekawa was a Japanese architect who worked on LeCorbusier office during the latest 1930s. In 1946, in association with a structural engineer and a professor of the Tokyo University, Maekawa founded PREMOS with the ambition to mass produce houses following Henry Ford's theories. The company was shut down in 1952.

before. The London carpenter H. Manning was producing ‘Portable Colonial Cottages’<sup>5</sup> in 1837 (Bergdoll and Christensen, 2008: 40). Between 1910 and 1930 the ‘Atholl Steel Houses’ company constructed over 100 houses and ‘British Iron and Steel Federation’ (BISF) houses delivered 36,546 houses designed by the architect Sir Frederick Gibberd and engineer Donovan Lee (O’Neill and Organ, 2016: 12-16; White, 1965: 39). These last two examples constructed on-site using factory produced steel frames. By that time timber housing was limited to the importation of houses from Canada and Scandinavia.

Most of the main Japanese housing manufacturers were founded during the 1950s and 60s, led by Daiwa with their ‘Pipe House’<sup>6</sup> model in 1955 (Noguchi *et al.* b, 2016: 342; Gann, 1996: 443; Johnson, 2007: 6). To Daiwa followed Sekisui House in 1960, Pana Home in 1963, Misawa Homes in 1967, SANYO Homes in 1969, Sekisui Heim in 1971 and Toyota started selling houses in 1977, all which remain active today (Johnson, 2007: 13; Noguchi *et al.* b, 2016: 354-357). This ‘boom’ came as a consequence of: the post-war housing deficit, expansion of Japanese industry in the housing market, use of light-steel in housing that came from an over-capacity in production after the Korean War, and due to the initiatives and promotion of the ‘Housing Loan Corporation’ and ‘Japan Prefabricated Construction Suppliers and Manufacturers Association’ (Duncan, 1973: 62; purekyo.or.jp; Johnson, 2007: 20; Barlow and Ozaki, 2005: 12). During the 1970s the Japanese government encouraged the improvement of industrialised housing through the ‘House 55 development Competition’ and by exhibiting the Misawa’s ‘Home Core’ model at the Osaka Expo (Noguchi *et al.* b, 2016: 342; misawa.co). Consequently, prefabricated house production reached a peak of 18% of the total market in 1994 and stabilised since then on 15% with an average of construction around 400,000 dwelling per year (Johnson, 2007: 11-20; Linner and Bock, 2013: 160).

In different circumstances, from 1944 to 1949, in the UK the Temporary Housing Programme financed the construction of over 155,000 prefabricated bungalows, which were subsidised by the ‘Ministry of Works’ and manufactured by companies involved in other sectors<sup>7</sup> (Vale, 1995: 1-2). None of these companies continued producing prefabricated houses after the programme, neither other companies such as BISF. During the following decades, some housing companies utilised non-traditional construction methods, like the Wimpey’s No-fines system, but remained as conventional housebuilders (BRE, 2002: 11).

Table 1. JPN and UK general comparison.

	Japan	UK
Population (millions)	127	66
GDP (trillion USD)	4.92	2.68
GDP from construction	£28,000	£26,000
Average dwelling life	33 years	60 years
Main land transaction by housebuilders	Land with permission	Speculation
Ownership rate	62%	61%
Historical housing peak	1972, 1987 — 1,800,000	1970 — 400,000
New buildings over the total annual domestic transactions	80%	5%

<sup>5</sup> The ‘Portable Colonial Cottages’ were grooved wooden posts embedded and bolted into a continuous floor plate.

<sup>6</sup> Daiwa’s ‘Pipe House’ was a compact shed composed by a pipe steel frame structure covered with corrugated steel sheets, inspired on bamboo structures capable to survive typhoons (daiwa.com).

<sup>7</sup> The 4 bungalow models were: **Acron** by Acron group, **Uni-Seco** by the Selection Engineering Co, **Tarran** by Tarran Industries and **Aluminium** by the Bristol Aeroplane Co., Weston-super-Mare, Vickers-Armstrong, Blackbourn Aircraft and A.W. Hawksley.

The continuity and constant improvement of the Japanese housing companies have allowed them to refine their manufacturing processes looking for more precise ways to accommodate customers' wants and needs as a marketing strategy. Between 1994 and 2003, houses delivered with photovoltaics (PV) in Japan increased from 539 to 52,863 houses (Noguchi, 2013: 167-168). Nowadays, Japanese companies include PVs and mechanical systems as standards and have launched zero energy and zero carbon models into the market. The following table is presented to emphasise some contextual similarities and differences between both contexts. Precisely, because customers were offered a virtuous choice married to a healthy profit margin for the manufacturer. This approach of product segmentation and upselling follows successfully practice in the automobile industry.

### **Relationship between land value and speculation in the construction process**

Relations between land commercialisation and construction has an effect on the type and level of sophistication of the construction processes. The UK housing industry relies on speculating over the land, making *traditional systems*<sup>8</sup> more profitable (Ball, 1983: 167). In Japan 'land speculation' does not guarantee profitability; therefore, Japanese housebuilders have developed refined competitive strategies through efficiency in production and investment on marketing (Barlow and Ozaki, 2005: 18; Johnson, 2007: 41).

The Japanese industry has been benefited from constant housing demand, due to short dwelling average life of 30 years and cultural desire for modernity (Barlow and Ozaki, 2005: 11). Moreover, Japanese people have strong attachments to the land, but not especially for their buildings, which induces housebuilders to accelerate procurement process to reduce customer's time between homes. In contrast, UK house developers hold stocks of land with outline planning permission, adjusting production in response to the economic cycle to maintain and increase the value of the land they own, process known as land-banking (Ball, 1983: 143). And even Japan and the UK have a similar ownership rate, new housebuilding in Japan represents around 80% of the total annual domestic transactions, highly different to UK's 5% (tradingeconomics.com; Barlow and Ozaki, 2005: 11).

Rapid replacement of the housing stock in Japan ask-us to perceive land separately from the constructed building. Land is more of a stable asset, while the dwelling is seen as a manufactured good. In the UK both land value and dwelling are seen as a single asset to the householder, and therefore, there is more resistance of disposing such an asset.

Table 2. JPN and UK Land value comparison. Prices are in GBP per square meter.

Data obtained from globalpropertyguide.com and dailymail.co, 2017.

		Empty plot	Existing Construction	New Construction
JPN	Osaka	990	2,090	3,840
	Tokyo	1,440	3,410	5,970
UK	UK average	*		2,215
	London	*		5,000

\*In the UK land is also sold as plots, but the price is referenced to the permitted construction.

Table 2 reveals that the price of the dwellings in Japan decreases over time as a consequence of the rapid replacement of houses, thus, stabilising the consumerist cycle. On the other hand, UK land values relate to its location, where the housing market is more dependent on macro-economic cycles.

<sup>8</sup> Professor Michael Ball refers to 'traditional systems' to on-site processes not based on pre-assembly components.

Therefore, the UK model is characterised by the acquisition of land by housebuilders before identifying customers. Therefore, land-banking in combination with traditional systems of constructions are considered more profitable; mainly because it allow housebuilders to conveniently adjust construction times. In Japan land is already owned by customers or sold to them under the condition to employ their services<sup>9</sup> (Johnson, 2007: 22).

### Comparison of selected companies

Japanese companies have been praised for their capacity to mass customise their products to allow customers to choose, and personalise their choices, from an arranged menu of options provided (Noguchi *et al.* a, 2016: 95; Piroozfar and Piller, 2013: 3). Therefore, housing companies utilise mass customisation processes, not only to satisfy the customer's needs more precisely but mainly as a marketing advantage. So, which would be the environmental advantages of using mass customisation processes? Is mass customisation the key to delivering zero energy houses? A selected range of companies from Japan and the UK were compared in the following table to bring up differences and similarities in the use of mass custom processes in relation to energy efficiency.

Table 3. JPN and UK housing companies' comparison.

Company	Japan				UK		
	Sekisui Chemical	Daiwa House	Sekisui House	Misawa homes	Scot-frame	Carbon Dynamic	Stewart Milne
Foundation	1971	1955	1960	1967	1987	2010	1975
Model	Modular	Modular	Modular	Modular	Panel	Modular	Panel
Structural Material	Wood and Steel frame	Wood and Steel frame	Wood and Steel frame	Light-concrete	Timber frame	Imported CLT	Timber frame
Design model	Custom catalogue	Custom catalogue	Custom made	Custom catalogue	Catalogue or bespoke	Bespoke	Bespoke
Net assets (M)	£3,980	£8,640	£14,730	£3,126	£11	-	£71
Factories	8	-	5	-	2	1	2
Employees	23,010	43,000	23,300	9,400	-	-	900
Dwellings built per year	13,240	9,894	15,300	12,800	1,500	<50	10,000*
Zero Energy Houses (total)	160,000**	13,423	19,000	-	***	-	***
Inclusion of renewables	yes	yes	yes	yes	***	might	***
Show-homes	yes	yes	yes	yes	no	no	yes

\*Measured in Units rather than in dwellings. Usually, a dwelling is composed of 10 units.

\*\*Sekisui "Smart Heim" models that include solar energy generation, not entirely net-zero energy.

\*\*\*Companies are not involved in the colocation of mechanical systems and renewables.

Construction companies in Japan are large conglomerates, where housing represents around 25% of their income. They have expanded from housing to real estate, residential management, rental housing, retail, resort, among others ([daiwahouse.co](http://daiwahouse.co); [misawa.co](http://misawa.co); [sekisuihouse-global.com](http://sekisuihouse-global.com)). Considering only the housing sector, the gap between the companies is reduced, Sekisui Heim Housing assets will be set in 1,600 million pounds employing 8,820 people, which is still almost ten times Stewart Milne's numbers.

<sup>9</sup> William Johnson define this phenomena as '*land with conditions*'.

UK's housing developers consider timber frame systems in combination with traditional construction to reduce costs and achieve better energy efficiency (O'Neill and Organ, 2016: 11 — Hashemi, 2013). Therefore, Scotframe and Stweart Milne, similar to other British timber frame manufacturers, are material manufacturers rather than housebuilders. However, an irony lies in the couple of off-site manufacture with slow traditional processes of applied brick, block or masonry cladding to buildings that erode the advantages timber frame may have in terms of time and efficiency.

### ***Modern Methods of Construction (MMC) and Sustainability***

Environmental benefits of MMC are well known: reduction of waste, controlled environment and precision over the production, associated with higher levels of airtightness, and as a consequence, more energy efficient dwellings. Companies in both contexts are utilising MMC. However, only Japanese companies are capable of delivering a high percentage of zero energy dwellings; which levels of energy performance and sales keep on rising. Therefore, the difference might not be present in producing in- or off-site, it will rather be in the capacity of the Japanese companies to provide an integrated service that is fully customer-oriented.

Despite strict environmental policies in Japan, companies have realised that delivering sustainable dwellings provide them with a commercial advantage. Sekisui Chemical increased the percentage of PV systems in their houses, from 32 to 46% from 2002 to 2003. Sekisui House launched their net-zero-energy detached dwellings in 2013, which ratio of delivery achieved 74% of their total sales in 2015. (Noguchi, 2013: 169; sekisuihouse-global.com). These companies constantly improve their dwelling quality through 'cost-performance' strategies<sup>10</sup> as it increases its demand, even this represents an approximately 8% higher cost than the national average (Noguchi, 2005: 26-28).

Moreover, both countries have stipulated targets on the reduction of energy and carbon emissions; Japan committed to reducing greenhouse gas emissions by 39% in the residential sector, and the government is targeting to implement zero-energy housing standards to all new houses built by 2020 (Sekisui House, 2016: 23). Similarly, the UK committed to reducing carbon emissions within the Kyoto Protocol and had<sup>11</sup> targeted that all new houses by 2016 to be zero carbon (Frankhauser *et al.*, 2009: 99; Ares, 2016: 3). The efforts in reducing the energy usage of a building by increasing its airtightness and material qualities are not enough to achieve the stipulated targets. Zero energy/carbon dwellings need to be capable of generating energy besides being energy efficient (HM Government 2008: 10). Therefore, companies that do not provide a proactive service installing renewables and efficient mechanical systems mitigate against zero energy/carbon houses.

### **Conclusion**

Japan and the UK have several similarities. Both are exporting economies with high levels of technical sophistication. After the Second World War both countries have chronically housing demand and opted for industrialised production processes as a solution. The UK as Japan has established targets to reduce their CO<sub>2</sub> emissions. However, only Japanese companies are at the forefront of commercialising industrialised air-tight dwellings equipped with renewables and energy efficient mechanical systems that meet the demands for sustainable housing

<sup>10</sup> 'Cost performance' is the ratio of earned value divided in actual costs. Business formula to increase the value of the product without substantially increasing its cost.

<sup>11</sup> In 2015 the Government in England withdrew the Code for Sustainable Homes and with it its 2016 targets. Some standards were/are-supposed-to-be added into Building Regulations.

(Noguchi, 2005: 28). The following table list the barriers MMC are confronting and possible beneficial crossovers Mass Customisation strategies could bring to the delivery of zero energy/carbon dwellings in the UK.

Table 4. Barriers and positive crossovers from the Japanese housing market in the UK.

<b>Barriers for MMC</b>	<i>Land price drives housing activity</i> — housebuilders find traditional methods of construction more profitable than industrialised ones.
	<i>Reputation</i> — events like the Ronan Point collapse negatively tagged industrialised housing, while Japanese prefabricated houses have been praised to their resistance to natural disasters.
	<i>Erroneous paradigms</i> — prefabrication in the UK has been promoted to reduce construction prices, which in reality is around 10% more expensive, while its sustainable advantages are still doubted (O'Neill and Organ, 2016: 12—Piroozfar <i>et al.</i> , 2012).
	<i>AID dependent</i> — support to off-site construction has suffered fluctuations depending on political visions.
	<i>Difficulties ensuring Economies of Scale and supply chain</i> (BRE, 2002: 21).
<b>Positive crossovers</b>	<i>Customer in control</i> — it increases social appealing and may <i>push-out</i> old negative stigmas.
	<i>Marketing paradigm</i> — mass customisation is a marketing sophistication that proved to be successful in other markets in the UK and in housing in Japan.
	<i>No need of high investments</i> — mass customisation rely more on marketing than in technology; therefore, manufacturing may remain <i>low-tech</i> .
	<i>Government independent</i>

Similar as in Japan, people in the UK is starting to associate MMC with quality and energy efficiency, adding pressure to modify construction policies in favour of MCC; however, this is rare to happen. Nevertheless, other successful practices of Japanese companies could be adopted in the UK without investing in costly technology. This study identified that Japanese housing manufacturers deploy **mass custom** strategies to deliver zero energy/carbon dwellings— where users can *informally* select from integral models. To apply mass custom strategies in the UK housebuilders have to shift from material to customer oriented perspective. Therefore, mass customisation of houses depend more on marketing than manufacturing.

## References

- ARES, E. 2016. Zero Carbon Homes. House of Commons Library.
- ASSOCIATION, JAPAN PREFABRICATED CONSTRUCTION SUPPLIERS AND MANUFACTURERS ASSOCIATION *An Introduction to Japan Prefabricated Construction Suppliers and Manufacturers Association* [Online]. Available: <http://www.purekyo.or.jp/English/index.html> [Accessed April 17 2017].
- ASSOCIATION, S. T. *Home page* [Online]. Available: <http://www.structuraltimber.co.uk/> [Accessed April 16 2017].
- BALL, M. 1983. *Housing policy and economic power: the political economy of owner occupation*, London, London: Methuen.
- BARLOW, J. 1999. From Craft Production to Mass Customisation. Innovation Requirements for the UK Housebuilding Industry. *Housing Studies*, 14, 23-42.

- BARLOW, J., CHILDERHOUSE, P., GANN, D., HONG-MINH, S., NAIM, M. & OZAKI, R. 2003. Choice and delivery in housebuilding: lessons from Japan for UK housebuilders. *Building Research & Information*, 31, 134-145.
- BARLOW, J. & OZAKI, R. 2005. Building mass customised housing through innovation in the production system: lessons from Japan. *Environment and planning A*, 37, 9-20.
- BERGDOLL, B., CHRISTENSEN, P., BROADHURST, R. & MUSEUM OF MODERN, A. 2008. *Home Delivery: fabricating the modern dwelling*, New York, New York: Museum of Modern Art.
- BRE 2002. Non-traditional housing in the UK— A brief review. In: ESTABLISHMENT, Commissioned by the Council of Mortgage Lenders. Written by Keith Ross of the Building Research Establishment (ed.). BRE.
- DAIWA. *Pipe House* [Online]. Available: <https://www.daiwahouse.co.jp/English/history/1960/pipe.html> [Accessed April 16 2017].
- DUNCAN, W. C. 1973. *U.S.-Japan automobile diplomacy: a study in economic confrontation*, Cambridge, Mass., Cambridge, Mass. : Ballinger.
- FRANKHAUSER, S., KENNEDY, D. & SKEA, J. 2009. The UK's carbon targets for 2020 and the role of the Committee on Climate Change. In: GIDDENS, A., LATHAM, S. & LIDDLE, R. (eds.) *Building a low-carbon future: The politics of climate change*. policy network.
- GANN, D. M. 1996. Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14, 437-450.
- GOVERNMENT, H. 2008. Definition of Zero Carbon Homes and Non-Domestic Buildings. In: GOVERNMENT, C. A. L. (ed.). London.
- HOUSE, S. *Global Leader* [Online]. Available: <http://www.sekisuihouse-global.com/solutions/01/>
- HOUSE, S. 2016. Sustainability Report 2016.
- JOHNSON, W. 2007. Lessons from Japan: A comparative study of the market drivers for prefabrication in Japanese and UK private housing development. UCL (University College London).
- LINNER, T. & BOCK, T. 2013. Automation, robotics, services: evolution of large-scale mass customisation in the Japanese building industry. In: PIROOZFAR, P. A. E. & PILLER, F. (eds.) *Mass Customisation and Personalisation in Architecture and Construction*. Oxon, UK: Routledge.
- MISAWA. *History of Misawa Homes Group* [Online]. Available: <https://www.misawa.co.jp/en/info/history.html> [Accessed April, 16 2017].
- NOGUCHI, M. Japanese Prefabricators' Means to Commercialize 'Mass Custom Homes' Equipped with Photovoltaic Solar Electric Systems. ACSA 2005 International Conference, 2005 Mexico City. 25-29.
- NOGUCHI, M. 2013. Commercialisation principles for low-carbon mass customised housing delivery in Japan. In: PIROOZFAR, P. A. E. & PILLER, F. (eds.) *Mass Customisation and Personalisation in Architecture and Construction*. Oxon, UK: Routledge.
- NOGUCHI, M., FORMOSO, C., G. DA ROCHA, C., ANDÚJAR-MONTOYA, M. D., BUNSTER, V., CAMERON, R. & IMAI, C. 2016a. Mass Customisation. In: NOGUCHI, M. (ed.) *ZEMCH: Towards the Delivery of Zero Energy Mass Custom Homes*. Switzerland: Springer Tracts in Civil Engineering.
- NOGUCHI, M., HIROTA, E., KIM, J.-T., FORMOSO, C., ALTAN, H., BELL, P., FRATTARI, A. & RISCALA, L. 2016b. ZEMCH Business Operation in Japan. In: NOGUCHI, M. (ed.) *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes*. Switzerland: Springer International Publishing.
- OZAKI, R. & LEWIS, J. R. 2006. Boundaries and the meaning of social space: A study of Japanese house plans. *Environment and Planning D: Society and Space*, 24, 91-104.
- O'NEILL, D. & ORGAN, S. 2016. A literature review of the evolution of British prefabricated low- rise housing. *Structural Survey*, 34, 191-214.
- PIROOZFAR, P., ALTAN, H. & POPOVIC-LARSEN, O. 2012. Design for sustainability: A comparative study of a customized modern method of construction versus conventional methods of construction. *Architectural Engineering and Design Management*, 8, 55-75.
- PIROOZFAR, P. A. E. & PILLER, F. T. 2013. *Mass customisation and personalisation in architecture and construction*, London, London: Routledge.
- PREFABRICATE.BLOGSPOT. 2016. Prefabrication experiments - 86 - Kunio Maekawa's PREMOS. *pref[FABRICA]tors* [Online]. Available from: <http://prefabricate.blogspot.co.uk/> [2017].
- SHAFIK, M. & MARTIN, P. The impact of procurement methods on the Scottish housebuilding industry. In: BOYD, D., ed. 22nd Annual ARCOM Conference, 2006 Birmingham, UK. Association of Researchers in Construction Management, 81-90.
- VALE, B. 1995. *Prefabs: a history of the UK temporary housing programme*, London, London: Spon.
- WHITE, R. B. & BUILDING RESEARCH STATION (GREAT BRITAIN) 1965. *Prefabrication; a history of its development in Great Britain*, London, H.M. Stationery Off.



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*Design to Thrive*

## Taxonomy of Construction Method Within the Urban Kampung in Bandung, Case Study: Tamansari District

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**Abstract:** Some characteristics of the *kampung* that relates to built environment are excessive density settlement, good social linkage between inhabitants, and thus they share spaces for spatio-temporal functions as well as build their social amenities and properties together. Tamansari District is one of them. It is located in a valley in the middle of town, distinguished by its steep contour and vast development without any 4-wheel vehicular access inside. Currently, it is developing to be rental housing for workers and students who want to live near their workplaces and campuses. For the small construction site, they even build a house until 4 stories. Further, because of the different accesses to the site, there are some variations in traditional construction method that still be practiced. This paper aims to generate taxonomy of the construction method and material used. Using its embodied energy as the reference compares the construction methods listed. The results will be mapped in two-dimensional graphics. It shows that construction method used in the site is related to its distance to the vehicular access. The farther away the site from the vehicular access, the simpler its construction method, and hence it has lower embodied energy.

**Keywords:** urban *kampung*, embodied energy, construction method, Bandung, Indonesia

### Introduction

UN-Habitat (2015) mentioned that over 90% of urban growth is occurring in developing countries with about 70 million new residents are living in the cities each year. There is estimation that over the next two decades, the urban population of the two poorest regions, South Asia and Sub-Saharan Africa will be expected to double, which lead to the increasing number of informal settlement dweller (as cited in Sembiring, 2016). In most cases of developing countries, there are inadequate methods to accommodate the demands of settlement for the urban poor with urban planning and design paradigms often exclude this lowest class in their plans (Gouverneur, 2015; Werthmann, 2009; Davis, 2006). This has lead into a wide spread of informal settlement.

In Indonesia, informal settlement mostly known as urban *kampung* Devas (1980) stated that urban *kampung* are informal, unplanned housing area which farm a large part of most Indonesian cities (as cited in Widjaja, 2013). Bandung as one of Indonesian big city has a significant area of urban *kampung*. Widjaja (2013) was also mentioned that urban *kampung* in Bandung are the essential urban ingredient and quantitatively serve as urban

primary unit. Therefore, it is important to understand the attributes of urban *kampung*. One of the attributes is how the building is constructed within the urban *kampung* area. Our study is to understand and classify buildings within the urban *kampung* area in view of its construction method and site context. Furthermore, the construction method could also be studied in relation to its embodied energy.

This paper aims to generate taxonomy of the construction method and material used. It is presumed that the two aspects are related to the construction site position from the vehicular access. Moreover, using its embodied energy as the reference compares the construction methods listed.

### ***Embodied Energy of Materials***

One of the analyses that can be done for Tamansari District is building's embodied energy in the district. Crowther (1999) defines embodied energy as the total energy used in the making of a building, including the direct and indirect energy. While, Li et al. (2007) states that embodied energy is the total energy involved from the extraction, manufacturing, to the final disposal of construction materials. The total energy that as stated by Crowther (1999) as well as Crawford et al. (2006), counts the direct energy, which is the energy used for the construction and assembly process, and the indirect energy, which is the energy of manufacturing the materials. For this study, the embodied energy of materials calculated is specific for the initial embodied energy of buildings in Tamansari District.

The embodied energy of materials has a major contribution to energy consumption of a building during its lifecycle (Bansal et al. 2014). Previous studies prove that that different building typology has a different embodied energy value, since each building typology tends to utilize different combination of materials (Dixit 2013). Further, some studies also show that embodied energy is not only driven by building type, but also construction type such as steel building, concrete building, timber building, or brick building (Cole 1998; Vukotic et al. 2010).

### **Methodology**

Construction method of buildings in Tamansari District is detailed in terms of material used. In order to classify them, the study utilises total embodied energy of materials used in the buildings. Thus, the study uses quantitative method. Overall, there are three steps conducted. Firstly, boundary of the area observed is stated. The location and boundaries of observation area is shown in Figure 1. This area is located at *Kelurahan Lebak Siliwangi*, Coblong Subdistrict, Bandung. It is approximately 3,500 m<sup>2</sup>. The area is selected because it represents the characteristic required for the research:

- Houses adjacent to vehicular access (Pelesiran Road) which is located in the downtown area, with connector access to two main roads (Cihampelas Road and the Tamansari Road) easily
- Houses along the alleys inside the urban *kampung*.
- Some inner sections comprise of houses that can only be accessed by pedestrians
- A strip of houses at Cikapundung riverside

The area of this study enclosed by Pelesiran Road, Cikapundung River, the Pelesiran 8th alley, and steep alley inside the urban *kampung*.

Secondly, the study classifies the buildings within the area of observation. The construction methods are grouped based on typology of buildings, land use, and the size of the house, as well as the building materials used. Also, an in-depth observation and interviews with local residents were carried out to identify the character of the location which will then be divided into different locations to look beyond the material used, as well as the processes that occurred during the period of the 90s to the growing trend now.

Thirdly, embodied energy materials of building in each classification are calculated. Embodied energy calculation is started by detailing the materials used in the building. This research uses Material Unit Analysis published by Indonesian Government. The unit of detailed materials are then converted to kilogram.

The embodied energy is calculated by using inventory of materials' embodied energy as a reference. However, there are many inventories of material's embodied energy, and thus the selection of a standard inventory for this study is critical. The variation of the inventory, and also its quality is caused by some parameters that Dixit (2013) defines as: System Boundary; Method of Embodied Energy Calculation; Energy Inputs; and Data Quality. In this paper, the inventory used is the Inventory of Carbon and Energy (ICE) from University of Bath. The ICE from the University of Bath applies five criteria in collecting their Embodied Energy data, which is not to differ from Dixit's Parameters. The criteria are: Approved Methodology; System Boundary; Origin of the Data; Age of the Data Source; and the Embodied Carbon (Hammond & Jones 2008). The results of each classification are then compared and analysed.

Material Profile: Concrete					
Embody Energy (EE) Database Statistics - MJ/Kg					
Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE
Concrete	122	2.91	8.68	0.97	92.50
Concrete, General	112	3.01	9.07	0.97	92.50
Unspecified	85	2.12	2.85	0.97	23.90
Virgin	27	6.02	16.24	0.59	92.50
Concrete, Pre-Cast	10	1.89	0.43	1.20	2.72
Unspecified	6	2.01	0.43	1.36	2.72
Virgin	4	1.72	0.42	1.20	2.19
Selected Embodied Energy & Carbon Values and Associated Data					
Boundaries	Cradle to Gate		Data Range	(+/- 30%)	Specific Comments
Material	Embody Energy - MJ/Kg		Embody Carbon - Kg CO2/Kg		
General Concrete	0.95		0.130		Selection of a specific concrete type will give greater accuracy, please see comments.
1:1:2 Cement:Sand:Aggregate	1.39		0.209		(High strength)
1:1.5:3	1.11		0.159		(used in floor slab, columns & load bearing structure)
1:2:4	0.95		0.129		(Typical in construction of buildings under 3 storeys)
1:2.5:5	0.84		0.109		
1:3:6	0.77		0.096		(non-structural mass concrete)
1:4:8	0.69		0.080		
REINFORCED CONCRETE (ICE CMC Model Values)					
For reinforcement add to selected coefficient for each 25kg steel reinforcement	0.26		0.018		For each 25 kg Steel per m3 concrete
EXAMPLE: Reinforced RC20 (See Below) with 100kg Rebar	2.12 (1.08 + 0.26 * 4)		0.241 (0.153 + 0.018 * 4)		

Figure 1 Data taken from the ICE, University of Bath

## Results and Discussion

### Taxonomy of the construction method

In view of its context, urban *kampung* mostly developed in organic manner. Due to its organic development, physically all the components and infrastructure are developed in non-standard dimension. Part of the infrastructure are accesses; the road, the alley, etc. Typically, there will be one main road in urban *kampung* and smaller local alleys connected

to the main road. Then, the settlement will develop in between the alley. Urban kampung settlement always grow significantly, along the way the spaces in between the houses most of the time will also serve as informal alley. It is very common in urban *kampung* that one somewhat go through someone's yard to go to the other side.

Our hypothesis is that the different types of accesses are affecting the method of construction. We studied samples at Pelesiran Road, Tamansari area. Most of the houses at Pelesiran Road are built individually. Based on the location and proximity to the main road, we could classify the houses into four categories.

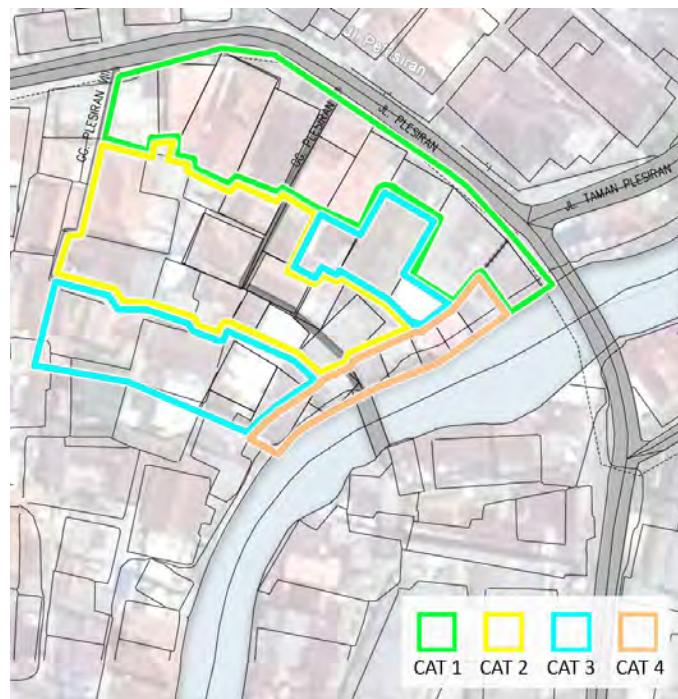


Figure 2 Site Location

#### *Category 1*



Figure 3 Category 1 Houses (Source: Personal Documentation)

Category 1 houses are more permanent and mostly had been converted into commercial use; local food stall, local convenient shop and boarding houses, etc. In view of building materials, houses in category 1 use bricks and reinforced concrete. Number of storey is varying from single storey to 3-storey house. Although the houses are more permanent, most of it still built individually and informally.

#### *Category 2*



Figure 4 Category 2 Houses (source: Personal Documentation)

In view of construction material, most of the category 2 houses are not as permanent as the category 1 ones. Typical 2-storey houses use brick and concrete construction at ground floor and timber construction at 2<sup>nd</sup> storey. Some are more permanent than the other, employing a timber structure at 2<sup>nd</sup> storey with combination of concrete slab for the floor.

#### *Category 3*



Figure 5 Category 3 Houses (source: Personal Documentation)

In this category, most houses are built using simple materials; mostly the ground floor were constructed with brick as load bearing wall and wood construction for floors and walls at the upper level, the height varies depending on the location and the needs of the family. The houses are located near to the alley access into the rear area of the arrangement of the main aisle and at the slope area where there is a significant differences in altitude and not accessible by motorbikes.

#### *Category 4*



Figure 6 Category 4 Houses (source: Personal Documentation)

The houses arrangement is positioned back to the river with a height of up to 4 floors. Architecture with a lower floor height at each level is built using materials and simple types of construction. They only reinforce the structure to the floor parallel to the pedestrian level

(on the second floor) using reinforced concrete. While the third floor upwards were developed with lighter materials (mostly wood, the floor using wooden planks on which casted with concrete or floor with teak block or wooden board that varied using soft or hard wood randomly). The construction on the third floor upwards also carried out if needed. What we can see along the river is a development of semi-permanent structure that was once dominated this area.

Table1.Taxonomy of the Construction Method in Pelesiran, Tamansari District

<b>Category</b>	<b>Type</b>	<b>Site Area (m<sup>2</sup>)</b>	<b>Construction Type</b>
<b>1</b>	<b>A</b>	<b>48.00</b>	1-storey, Concrete Structure, Brick Wall, Clay Roof-tile
	<b>B</b>	<b>48.00</b>	2-storey, Concrete Structure, Brick Wall, Clay Roof-tile
<b>2</b>	<b>A</b>	<b>21.00</b>	2-storey, Concrete Structure, Brick Wall, Clay Roof-tile
	<b>B</b>	<b>21.00</b>	2-storey, Concrete Structure, Brick Wall on the 1st floor, timber wall on the 2nd floor, Clay Roof-tile
	<b>C</b>	<b>21.00</b>	2-storey, Concrete structure on the 1st floor, timber structure on the 2nd floor, Brick Wall on the 1st floor, timber wall on the 2nd floor, Clay Roof-tile
	<b>D</b>	<b>21.00</b>	3-storey, Concrete Structure, Brick Wall until 2nd floor, timber wall on the 3rd floor, Clay Roof-tile
	<b>E</b>	<b>21.00</b>	3-storey, Concrete structure on the 1st floor, timber structure on the 2nd and 3rd floor, Brick Wall until 2nd floor, timber wall on the 3rd floor, Clay Roof-tile
	<b>F</b>	<b>21.00</b>	5-storey, Concrete Structure, Brick Wall on the 1st floor, timber wall on the 2nd floor, Clay Roof-tile
<b>3</b>	<b>A</b>	<b>21.00</b>	2-storey, Concrete Structure, Brick Wall on the 1st floor, timber wall on the 2nd floor, Asbestos Roof
	<b>B</b>	<b>21.00</b>	2-storey, Concrete structure on the 1st floor, timber structure on the 2nd floor, Brick Wall on the 1st floor, timber wall on the 2nd floor, Asbestos Roof
	<b>C</b>	<b>21.00</b>	3-storey, Concrete Structure, Brick Wall until 2nd floor, timber wall on the 3rd floor, Asbestos Roof
	<b>D</b>	<b>21.00</b>	3-storey, Concrete structure on the 1st floor, timber structure on the 2nd and 3rd floor, Brick Wall until 2nd floor, timber wall on the 3rd floor, Asbestos Roof
<b>4</b>	<b>A</b>	<b>21.00</b>	3-storey, Concrete Structure, Brick Wall until 2nd floor, timber wall on the 3rd floor, Asbestos Roof
	<b>B</b>	<b>21.00</b>	3-storey, Concrete structure on the 1st floor, timber structure on the 2nd and 3rd floor, Brick Wall until 2nd floor, timber wall on the 3rd floor, Asbestos Roof
	<b>C</b>	<b>21.00</b>	4-storey, Concrete structure on the 1st and 2nd floor, timber structure on the 3rd and 4th floor, Brick Wall until 2nd floor, timber wall on the 3rd and 4th floor, Asbestos Roof

### **Total Embodied Energy of Building Materials**

The embodied energy (EE) of materials calculation results is shown in the table below. Based on the calculation, the highest value of total embodied energy is recorded in Category 1, Type B, which has about 179.1 GJ embodied energy. Meanwhile, the lowest value is shown in the Category 3 Type B houses with 53.2 GJ. Clearly, building area relates strongly to total embodied energy of materials.

However, in the case of two similar building areas, variation occurs in the different construction type. For instance, although the Category 3 Type A and B buildings have the same area, they are difference in EE value. This indicates the contribution of material selection in embodied energy value. Moreover, if the EE is viewed in terms of energy efficiency per unit area, the highest efficiency is shown by Category 3 Type B. It is in line with lowest total embodied energy value. Nonetheless, the worst efficiency is displayed by

Category 2 Type A house. The building uses concrete and brick as the main construction materials, and with its smaller building area, it becomes less efficient than the others.

Table2.Embodied Energy Calculation Result

Category	Type	Building Area (m2)	Total Embodied Energy of Materials (MJ)	Total Embodied Energy of Materials (MJ/m2)
1	A	48.00	98,264.83	2,047.18
	B	96.00	179,072.71	1,865.34
2	A	42.00	104,574.97	2,489.88
	B	42.00	59,064.91	1,406.31
	C	42.00	55,893.91	1,330.81
	D	63.00	90,938.29	1,443.46
	E	63.00	83,147.91	1,319.81
	F	105.00	162,807.67	1,550.55
3	A	42.00	56,412.19	1,343.15
	B	42.00	53,241.19	1,267.65
	C	63.00	90,938.29	1,443.46
	D	63.00	83,147.91	1,319.81
4	A	63.00	90,938.29	1,443.46
	B	63.00	83,147.91	1,319.81
	C	84.00	151,332.67	1,801.58

Further analysis can be done by mapping the EE value to the observation area (Figure 7). The map reveals that EE value distribution is not strongly related to the building's location. Indeed, buildings located near the main access have higher EE value. But, for other categories, the total EE Value spreads randomly. This finding shows that accessibility of the building's site does not really drive the material selection by the people.

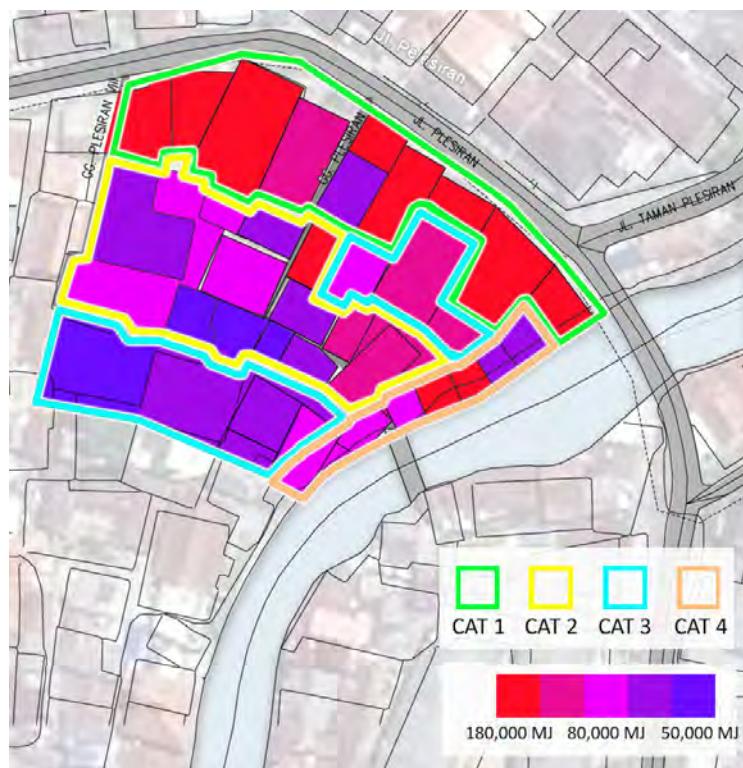


Figure 7 Embodied Energy in each category

## **Conclusion**

Taxonomy of construction method and materials in Tamansari District had been formulated. They are categorised based on the location and proximity to the main road. Category 1 is houses that facing the connector road, which can be accessed by vehicular, i.e. cars, motor cycle, etc. Category 2 is houses that located along the secondary alley that connects directly to the main road and can only be accessed by pedestrian or motor cycle. Then Category 3 is houses that located at the inner area which has very limited access to pedestrian. The alley characteristics of alleys in Category 3 are; narrow width, steep contour, cramped arrangement of houses. The last one is Category 4, which are houses that located along the riverside.

Furthermore, based on those classifications, the embodied energy of materials is calculated. From the results, it can be concluded that building's area materials selection relate strongly to total embodied energy. Further analysis by mapping the EE value to the observation area reveals that EE value distribution is not strongly related to the building's location. Buildings near the main access have higher EE value, but it is not the case for buildings in the Category 2 to 4. The EE value seems uniformly distributed. Since, there is not much to do with the building's site area, so the EE value is mostly determined by materials selection. Thus, this implies variations in people's selection of building materials.

## **Limitation**

Inventory of material's embodied energy used in this study is not originally from Indonesia. Thus, the results of EE calculation in this study may not reliable to real condition. Also, energy used in transporting the materials is not considered in this study. It may give different results if transportation is being considered.

## **References**

- Bansal, D., Singh, R. & Sawhney, R.L., 2014. Effect of construction materials on embodied energy and cost of buildings — A case study of residential houses in ... Energy & Buildings, 69(May 2016), pp.260–266. Available at: <http://dx.doi.org/10.1016/j.enbuild.2013.11.006>.
- Cole, R.J., 1998. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Building and Environment, 34(3), pp.335–348.
- Crawford, R.H. et al., 2006. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renewable and sustainable energy reviews, 10(6), pp.559–575.
- Crowther, P., 1999. Design for disassembly to recover embodied energy.
- Dixit, M.K., 2013. Embodied Energy Calculation: Method and guidelines for a building and its constituent materials.
- Dixit, M.K., Culp, C.H. & Fernández-Solís, J.L., 2013. System boundary for embodied energy in buildings: A conceptual model for definition. Renewable and Sustainable Energy Reviews, 21, pp.153–164.
- Hammond, P.G. & Jones, C., 2008. INVENTORY OF CARBON & ENERGY ( ICE ).
- Li, K. et al., 2007. Development of a framework for quantifying the environmental impacts of urban development and construction practices. Environmental science & technology, 41(14), pp.5130–5136.
- Vukotic, L., Fenner, R.A. & Symons, K., 2010. Assessing embodied energy of building structural elements. In Proceedings of the Institution of Civil Engineers-Engineering Sustainability. Thomas Telford Ltd, pp. 147–158.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A teaching method for heat conduction and thermal inertia within a sustainable architecture framework

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**Abstract:** Development of sustainable buildings implies design of passive systems for indoor acclimatization. For this reason, building architects are required to understand physics phenomena related to the interaction between building envelopes and solar radiation. These phenomena are intimately associated to construction materials' optical, thermal, and mechanical properties. In an effort to prepare its students in an integrated way, the School of Architecture of the National Autonomous University of Mexico is in the process of equipping its Sustainable Construction Laboratory (LES), where these physics phenomena will be taught in a practical way and through experimentation. One of the most important processes resulting from the interaction between building envelopes and solar radiation is heat transfer. Heat transfer begins when the envelope heats up and ends until the produced heat intervenes with indoor acclimatization. The student of Architecture needs to distinguish between two main heat transfer processes: one stationary which determines matter conductivity coefficient, and one dynamic when heat is conducted from the surface exposed to the Sun towards the interior. Dynamic heat transfer is a function dependent on time which implies thermal inertia. This work shows the didactic equipment developed in the Sustainable Construction Laboratory to teach these two phenomena.

**Keywords:** heat transfer, building envelope, didactic device

### Introduction

A building envelope acts as the frontier between the exterior and the interior of an architectural space designed and constructed to provide humans wellness and protection for his development. Building envelopes modulate the amount of energy required at the interior of a space to heat or cool a building for thermal and visual comfort. Because the envelope of a building is the layer that directly interacts with solar radiation, it is during its design process that the methodology for heating or cooling a building must be determined.

Passive indoor cooling or heating methods are determined by the thermal properties of the building envelope construction materials. Thermal resistance of a material determines the amount and speed of the thermal energy being transferred from the outside to an indoor space and vice versa; thermal mass determines the amount of energy the material is able to store and the amount of energy it is able to release. These two thermal properties directly relate to building heat gains and losses.

In general, thermal resistant materials are light and have low density. In contrast, high thermal mass materials have high density, and therefore, high capacity to absorb and accumulate, to later slowly release thermal energy. Many construction materials have both properties: certain thermal resistance and certain thermal mass. However, one usually

dominates over the other, and indoor thermal conditions depend on how these thermal properties are used.

The way thermal mass materials absorb, store, and release thermal energy, describes a thermal inertia to indoor temperature fluctuations, by offsetting indoor temperature variations with respect to outdoor temperature variations due to the changing solar radiation intensity through the day. When implementing indoor passive acclimatisation strategies in climates where temperature fluctuations vary by at least 10°C, as the case of Mexico City's climate, a correct understanding of thermal inertia is fundamental in conceiving energy efficiently designed buildings.

### **Sustainable Buildings Laboratory**

In its effort to prepare its students from an integral view, the National Autonomous University of Mexico (UNAM) School of Architecture (FA) is in the process of consolidating its Sustainable Buildings Laboratory (LES). The thermal properties measurement device, presented in this work, is part of this laboratory to experiment with thermal energy transfer in both, thermal resistant materials and high thermal inertia materials. In order to understand the thermal resistance property of a construction material it is important to know its thermal conductivity coefficient, and therefore, the experimental process is a stationary regime. On the other hand, in order to determine thermal inertia behaviour, it is important to analyse thermal conduction in a material from a dynamic point of view based on a time-dependant experiment.

To describe how the thermal properties measurement device works, it is important to first determine the physics principles of heat conduction.

### **Stationary Regime**

Experimentally, stationary heat conduction is established with a homogeneous parallelepiped material between two plates in contact with two parallel faces (of the parallelepiped) that determine temperatures  $T_1$  and  $T_2$  at the edge-faces of the parallelepiped. If the plates are at least the same size as the parallelepiped faces, and  $T_1 > T_2$ , a temperature difference, between them, is established. If  $T_1$  is maintained constant by a heat source, and  $T_2$  by an infinite heat sink, a stationary heat flux perpendicular to the parallel faces is established. The heat ratio per time unit is described by the following equation:

$$H=Q / \Delta t$$

where  $H$  is heat flux, and  $\Delta t$  is time difference.

Under these conditions, the following can be established:

$$H = \lambda A \frac{T_1 - T_2}{L} \quad (1)$$

where  $\lambda$  is the thermal conductivity coefficient,  $A$  is the faces area at  $T_1$  and  $T_2$  temperatures, and  $L$  is the distance between the faces (Figure 1).

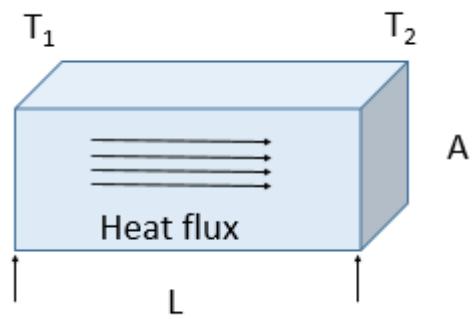


Figure 1. Heat flux.

By knowing the size of the sample and calculating the heat flux  $H$ , the thermal conductivity coefficient  $\lambda$  can be determined (Resnick et al, 1992).

The ASTM C177-97 norm (ASTM, 1997), which has been proven to be very reliable, was developed based on this principle. The thermal properties measurement device, described in this work, takes this norm as reference for its implementation. Figure 2 schematically describes its components.

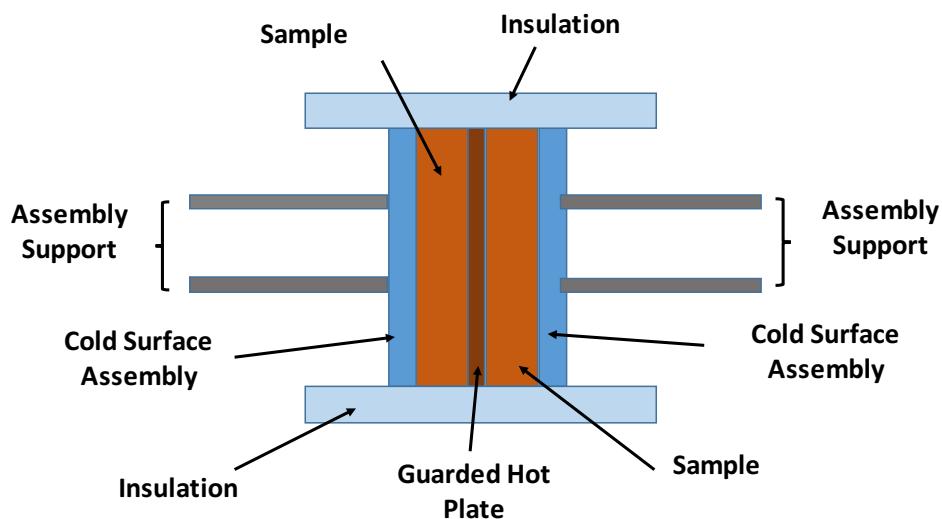


Figure 2. Thermal properties measurement device components configuration for stationary regime experimental setup.

### Dynamic Regime

Different from thermal resistance, thermal inertia relates to variation in the way heat is transferred from the outside to the inside —and vice versa— of an architectural space through the building envelope. Based on the outdoor day-night temperature variation cycle, building envelope thermal inertia has a thermal damping and lag effect towards indoor temperatures. These effect reduces indoor temperature fluctuations, and delays heat transfer through the envelope resulting in higher indoor temperatures (release of absorbed

heat) when outside temperatures begin to decrease, and in lower indoor temperatures (heat absorption and storage) when outside temperatures begin to increase. For passive indoor acclimatisation, it is desirable to lag thermal release towards the interior when outside temperatures are descending.

Within the objective of determining the amount of thermal damping and lag, the potency of the heating plate varies cyclically simulating outdoors temperature variations and therefore, temperature variations on one of the sample faces, leaving the opposing face temperature to vary “freely”. Variation of the heating plate potency is regulated with a pulse wave modulator (PWM), and free temperature evolution of the opposed sample face is achieved when cooling plates are separated 5 cms. from it and exposed to ambient temperature (figure 3).

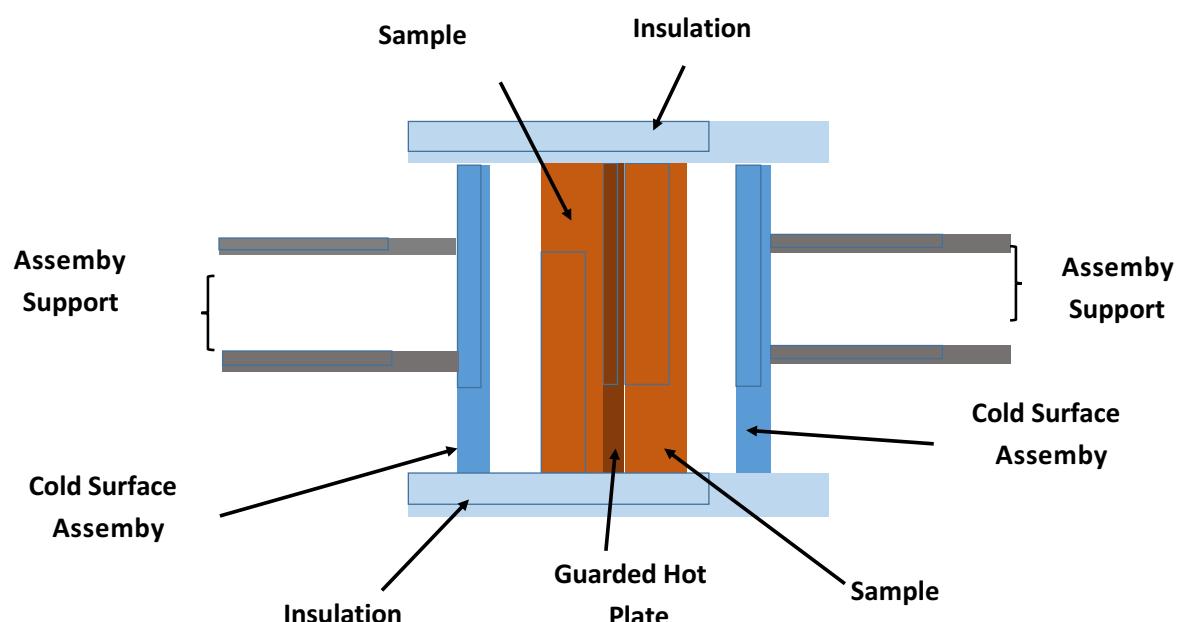


Figure 3. Thermal properties measurement device components configuration for dynamic experimental setup.

### Stationary Regime (Experimental Device)

As part of the experimental device body, refractory bricks with a 0.20 W/m-K thermal conductivity were chosen; a 0.20 W/m-K thermal conductivity is lower than the thermal conductivity of most construction materials. The hot plate endures a potency of up to 500W, and a 130 Ω electrical resistance. Using the PWM, electrical pulses are modulated and therefore, line voltage variated from 0 to 120 V and electrical current from 0 to 0.90 A (figure 4).

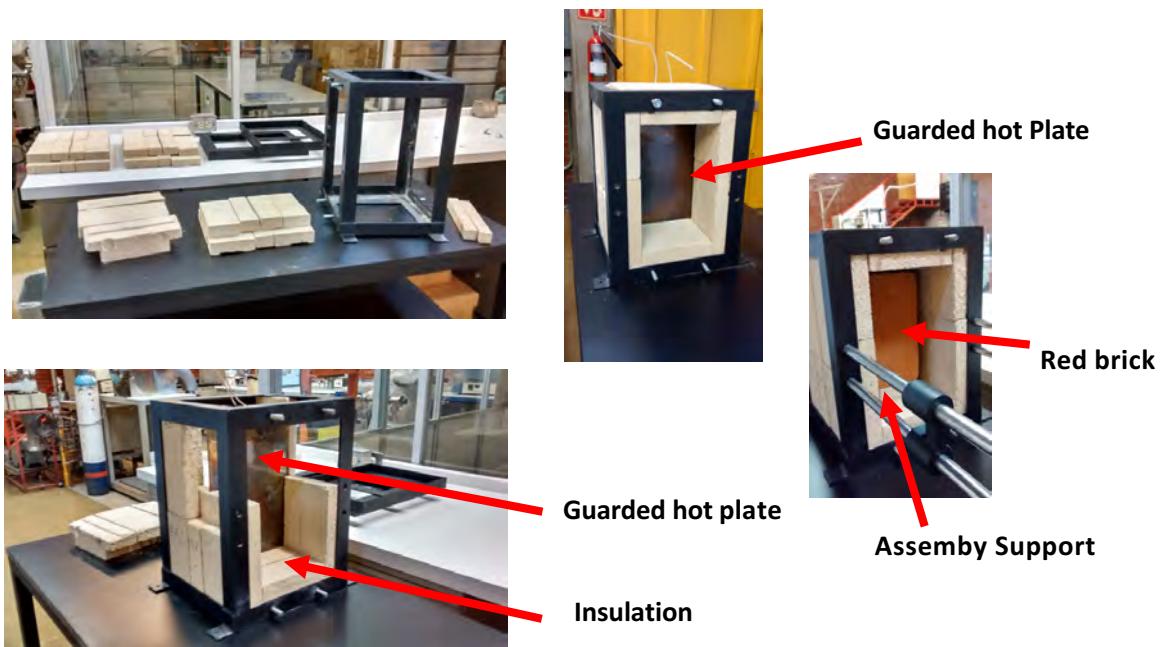


Figure 4. Guarded hot plate in the experimental device.

The cold plate is made of copper (Cu) with a 0.90 cm thickness; it is provided with circulating cooling water and thermocouples with springs for a better contact with the sample (figure 5).

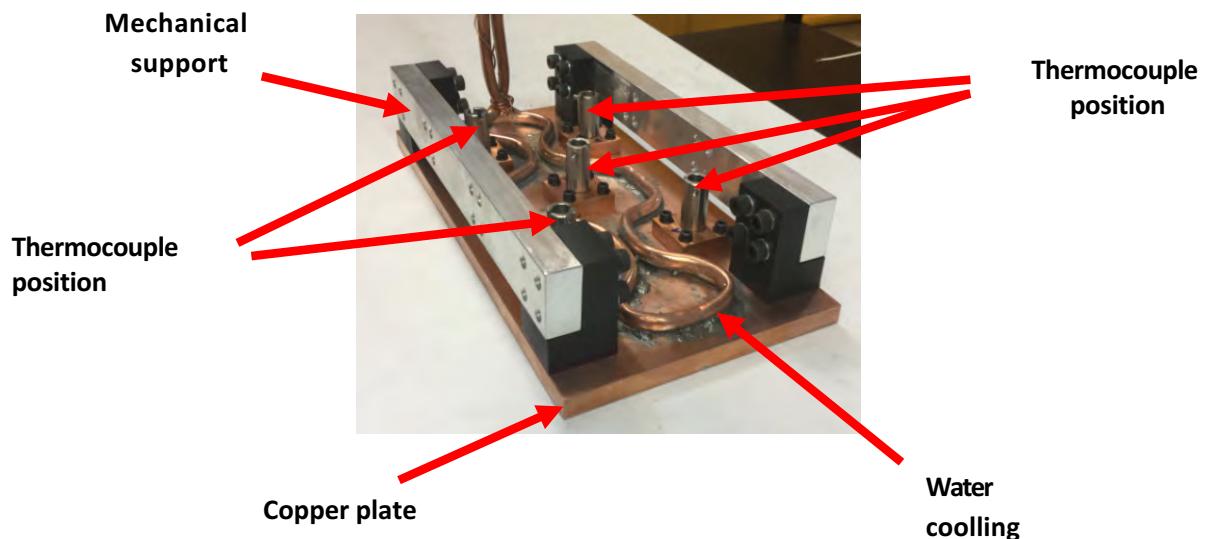


Figure 5. Cold plate in the experimental device.

## Red Brick Study

Commercial Mexican red brick was studied under the stationary and the dynamic regime to determine its conductivity coefficient and its thermal mass.

Temperatures  $T_1$  and  $T_2$  were measured to calculate the temperature difference  $\Delta T$  for different potencies of the heater:

$$\Delta T = T_1 - T_2$$

Three conductivity measurements were taken at approximately 10 degree (Kelvin or Celsius) intervals. The thermal conductivity results are shown in figure 6.

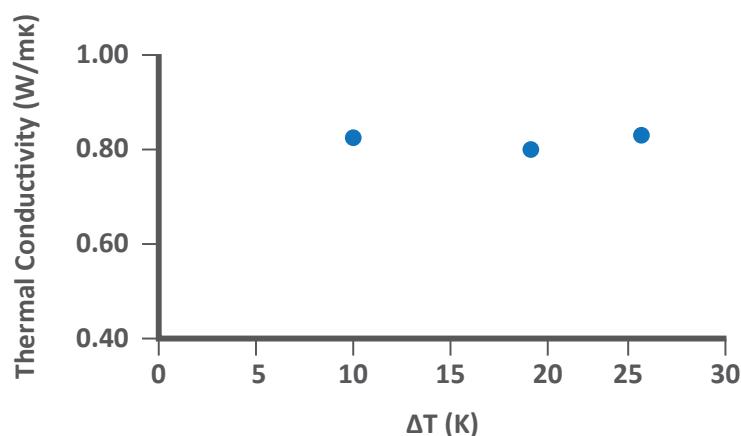


Figure 6. Conductivity measurements of the red brick taken with the experimental device.

The average value was of:

$$\lambda = 0.820 \text{ W/mK}$$

The brick thermal mass behaviour is shown in figure 7.

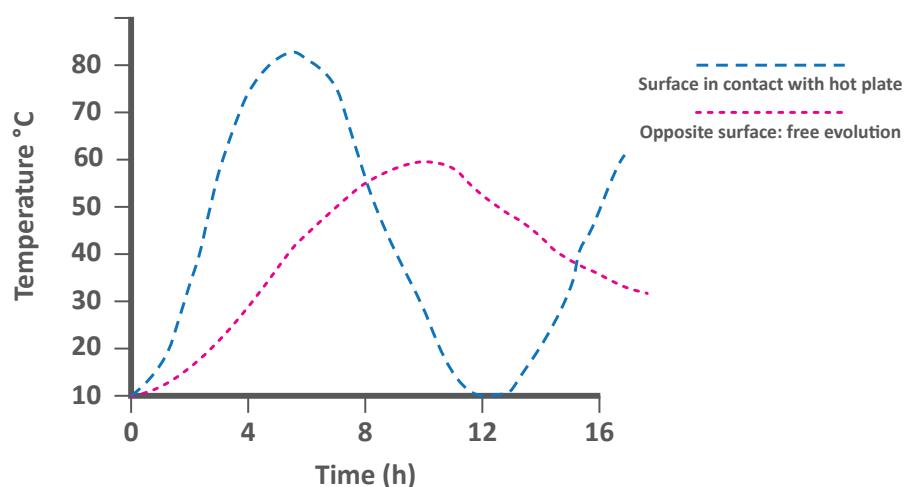


Figure 7. Red brick thermal mass behaviour.

## **Conclusions**

With this experimental device the thermal conductivity coefficient and the thermal mass behaviour of construction materials can be determined. These two properties play a key role in indoor building acclimatization, and should be taken into account during the building envelope design process. Therefore, the architect needs to understand these two concepts in order to apply them correctly when designing acclimatization passive systems. Its easy management allows students to experiment with both stationary and time dependent heat conduction. Dominium of both heat conduction regimes will help the future architect to design passive systems for indoor acclimatization in an optimal way.

## **Acknowledgements**

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## **References**

- Resnick, R., Halliday, D. and Kenneth, S.K. (1992). *Physics*. Fourth Edition. New York: John Wiley and Sons, Inc.
- American Society for Testing and Materials (1997). *ASTM C177: Standard Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot-Plate Apparatus*. Washington, D.C.: American Society for Testing and Materials (ASTM).



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Evaluation of slab-edge insulation on energy saving for heating and cooling slab-on-ground houses

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**Abstract:** The purpose of this study was to investigate the appropriate utilization of slab-edge insulation and the corresponding savings in operational energy by using data collected from two existing full scale housing modules with typical slab-on-ground footing systems. In this study, an experimental investigation and a theoretical analysis were carried out simultaneously. For the experimental investigation, one of the modules was retrofitted by installation of insulation at the edges of the slab, the other module slab edge (without insulation) was used as a parallel experiment. Fifty-eight sensors were arranged at the upper slab surface and the edge surface of the slab to monitor heat flow effects. There were auxiliary heating and cooling systems in the two housing modules to maintain a constant indoor temperature. The data of temperature, heat flux and operational energy over an eight-month period indicated that the slab-edge insulation had obviously decreased the energy consumption of the insulated housing module. In the numerical analysis, a transient two-dimensional Finite Volume Method (FVM) model was developed for the analysis of the effects of slab-edge insulation. An FVM, analysis was then carried out to evaluate the thermal performance of slab-edge insulation of various sizes and at different positions.

**Keywords:** Heat transfer, slab edge, insulation, in-situ experiment, numerical simulation

### Introduction

Australian households are directly responsible for about one-tenth of Australia's greenhouse gas emissions (Statistics, 2016). On the background of improving energy efficiency, the effective use of housing insulation has attracted significant research in recent years. Various insulation materials (for example: glass wool batts, extruded polystyrene) have been used in residential households to maintain a comfortable living environment to reduce the need for an auxiliary heating/cooling system or to minimise the energy consumption. Normally, insulation materials are used in the roofing system, the internal surface of walling systems, or in the cavity of masonry walls. A review of previous work (Hagentoft, 1988) (Neymark et al, 2008), found that 15% to 60% of residential energy consumption can be attributed to the heat transfer through the ground floor. Furthermore, the proportion of energy flow through an uninsulated floor can even contribute up to 67% of the overall energy flow of a building when the upper structure of the building was well insulated (Shipp, 1982). However, there has only been a small amount of theoretical analysis and in-situ experimental studies on the energy efficiency of an insulated slab for slab-on-ground housing, especially for houses in Southern Hemisphere countries. In the present study, the two existing full-scale testing houses on the campus of the University of

Newcastle, Australia were used to study the influence of slab edge insulation on household energy consumption. One of the test housing modules was insulated around the slab edges with XPS (Extruded Polystyrene) strip board, with the other being left with the slab edge uninsulated. Twenty-five thermocouples and four heat flux sensors were utilized in each testing house to monitor heat flows. Numerical simulations were conducted in parallel, with the experimental results being used to verify the analytical model. The model was then used to investigate the influence of slab edge insulation with different sizes and positions.

### Description of the test houses and instrumentation

The study involved the monitoring of the behaviour of two full scale housing modules (6m x 6m in plan) under a range of seasonal conditions and formed part of a larger, wide ranging 15-year study of the thermal performance of Australian housing (Page et al). The modules were constructed on the campus of the University of Newcastle (latitude 33°S) (see Figure 1) with a square floor plan of 6m x 6m and spaced 7m apart to avoid shading and minimise wind obstruction.



Figure 1. N-Module (on right) and F-Module (on left)

With the exception of the slab edge insulation, the other influencing factors such as windows, roof type, curtains, carpet, and room ventilation of the two buildings were of identical construction. The buildings were built on a concrete slab on ground and the northern wall of the buildings was perpendicular to astronomical north. Both buildings had a height of 2450mm. In each case, a typical slab on ground footing system was used to investigate the influence of slab edge insulation. XPS strip boards were firmly adherent to the vertical surface of the slab edges of one of the two modules (N-Module). To allow a direct comparison, the other housing module (referred to as the 'F-Module') was not insulated around the slab edges. The details of the slabs and the installed insulation are shown in Figure 2 and Figure 3.

There are many types of material when it comes to efficiently insulating new buildings or retrofitting old ones, including timber, polystyrene (PS), mineral wool, etc. Extruded polystyrene foam (XPS) is a commonly used material, and consists of closed cells. It therefore offers good surface roughness and higher stiffness. It is comparatively denser and therefore more water resistant, and has a better level of thermal performance (namely lower conductivity) compared to other rigid insulating materials. With consideration of the above favourable characteristics, XPS was selected to insulate the slab edges of the N-Module. As shown in Figure 2 and Figure 3, two vertical insulation boards: 30mm (thickness) x 150mm (depth) were installed at different depths around the slab edges (see XPS1, XPS2 in Figure 3). Another horizontal insulation board: 120mm (width) x 30mm (thickness) was

located next to the slab edges (see XPS3 in Figure 3). The thermal properties of XPS, the slab concrete and the foundation soil are listed in Table 1.

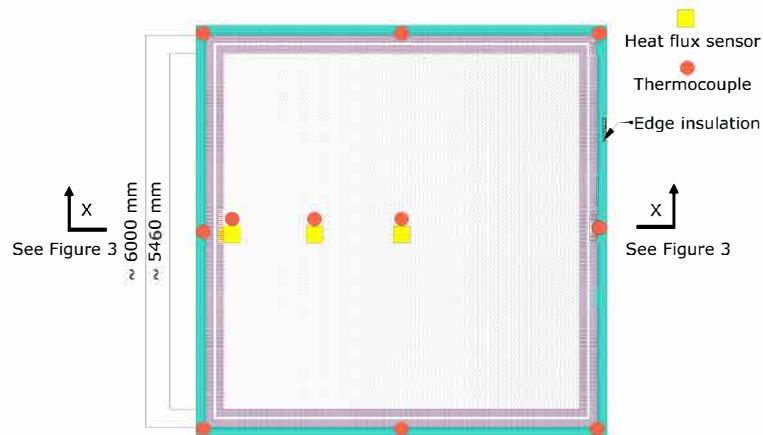


Figure 2. Floor plan of testing module

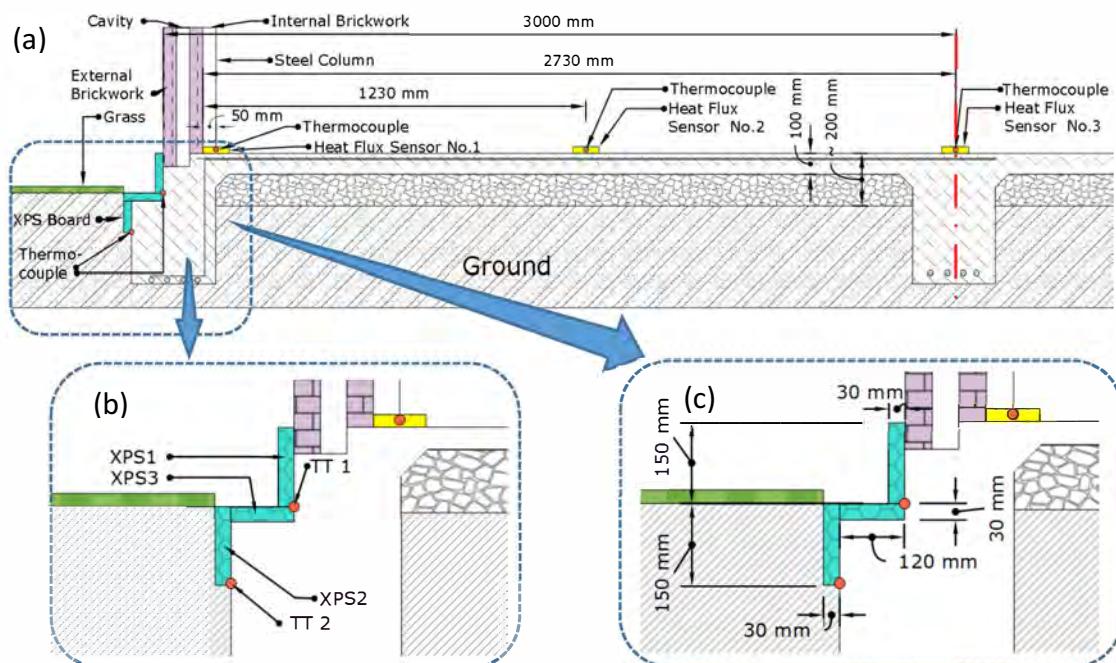


Figure 3. Part section X-X

Table 1. Thermal properties of XPS, concrete slab and foundation soil

Materials	XPS	Concrete	Soil
Thermal conductivity (W/m·K):	0.028	1.449	1.205
Density (kg/m <sup>3</sup> ) x Specific heat capacity (J/kg·K)	79861.5	2112000.0	1613000.0

### Details of instrumentation

In order to collect accurate and comprehensive temperature and heat flux data, twenty-five T-type thermocouples and four square metal heat flux sensors were installed on the upper and edge surfaces of the two floor slabs (as shown in Figure 2 and Figure 3). The thermocouples on the slab edge surface were installed at locations around the slab perimeter, and for each slab edge thermocouple there was a corresponding thermocouple

located on the underside of the slab. On the upper surface of the slab, the thermocouples and heat flux sensors were installed along the central axis in the West to East direction. Data were collected every 300 seconds 24/7 by means of a “DataTaker DT600” data logger

### **Experiment conditions**

The thermal response of the slab was assessed with the interior condition of each module in a ‘controlled’ state, with the interior temperature maintained within a pre-set range of 18 to 24 degrees centigrade using a cooling/heating system with the required energy usage being measured. A heating/cooling fan coil unit for this purpose was installed in each of the building modules as shown in Figure 4.



Figure 4. Water chiller (on left) and fan coil (on right) unit

### **Analysis of experimental results**

#### ***Temperature fluctuations at different depth***

Temperature fluctuations of the concrete slab edge were measured by thermocouples at location TT1 and TT2 (see Figure 3(b)) over a period of eight months. By averaging the values of temperature at eight positions around the slab edge perimeter, temperature fluctuations on the slab edges at TT1 and TT2 in four typical weeks were obtained as shown in Figure 5 to 8. By comparing the temperature fluctuations of the slab edges at different depths between the N-Module and F-Module in typical weeks, it can be seen that without slab edge insulation, the daily temperature fluctuation on the slab surface of the F-Module at TT1 was approximately 3 to 5 times greater than that for the slab with edge insulation in the N-Module. The difference in temperature fluctuation between the two testing modules on the lower position TT2 was similar to the TT1 situation but comparatively smaller. Energy flow through the slab depends on the temperature gradient between the slab edge and upper concrete floor surface. When the indoor environment is in a ‘controlled’ state, the smaller temperature fluctuation of the slab edge surface indicates that there is less energy lost through the slab.

It should also be noted that with increasing depth, the temperature fluctuation on the vertical slab surface decreased dramatically for both modules. Hence the effect of insulation at a deeper position was less efficient than the insulation closer to the ground surface.

In the summer period, the daily temperature difference between the interior and slab edge surface was biggest. Hence, when the module was in a ‘controlled’ state, more energy would be lost in summer than in the other three seasons. This was because the annual average ground surface temperature in the Newcastle area was higher than the pre-set room temperature. The results of this experiment and the results of the following numerical

simulation analysis, indicate that the strategies to install slab edge insulation need to be closely related to the climatic conditions.

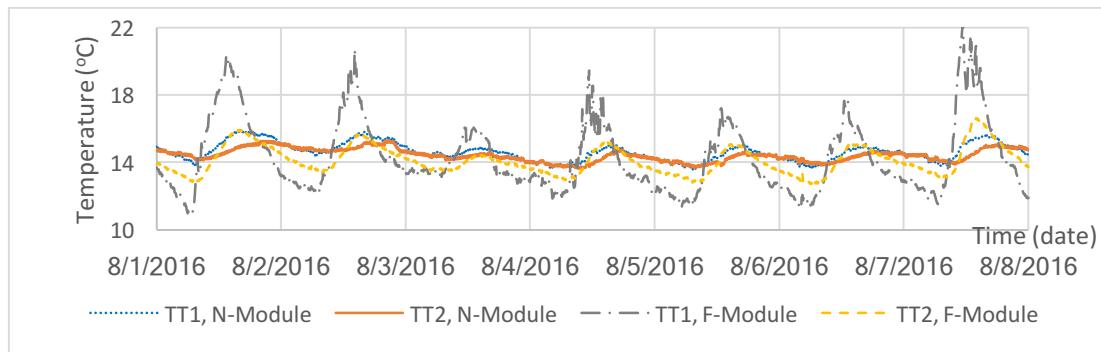


Figure 5. Temperature fluctuations at different slab vertical edge surface depths in a typical winter week

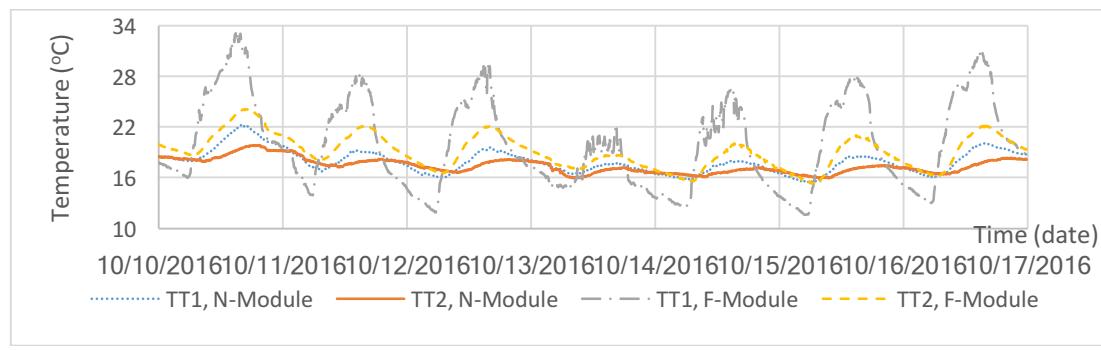


Figure 6. Temperature fluctuations at different slab vertical edge surface depths in a typical spring week

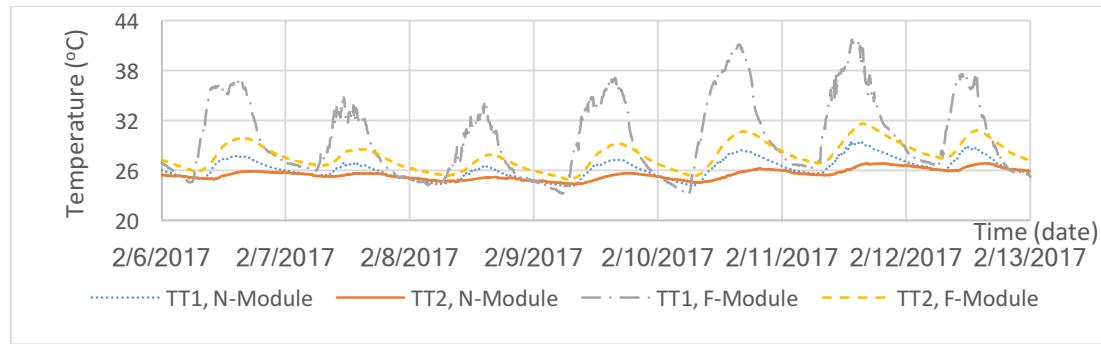


Figure 7. Temperature fluctuations at different slab vertical edge surface depths in a typical summer week

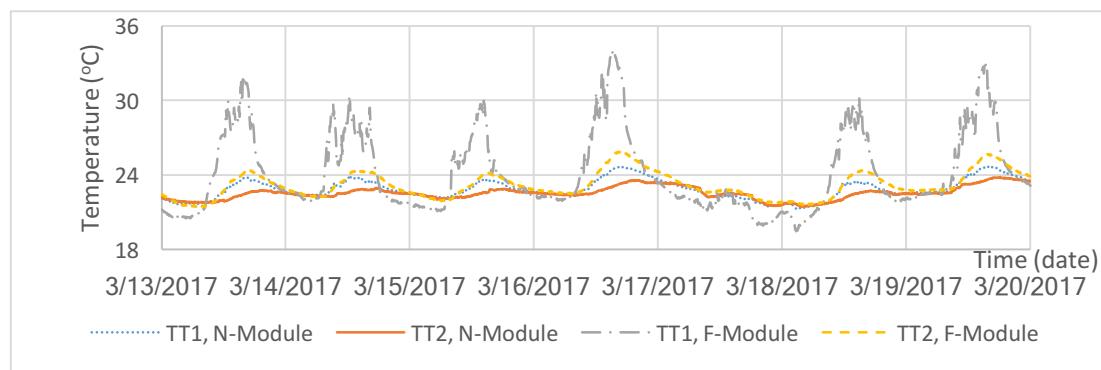


Figure 8. Temperature fluctuations at different slab vertical edge surface depths in a typical autumn week

### **Temperature fluctuations at different directions of the slab edges**

Based on the analysis of temperature fluctuation in the four seasons, the heat transfer through the slab in summer was the most significant. Therefore the temperature fluctuation of a typical summer week was chosen for analysing the nature of the temperature distribution and fluctuation in the different plan directions of the slab.

To compare the amplitude of the temperature fluctuations in the two modules (as shown in Figure 9 and Figure 10), the amplitudes of the slab surface temperatures with edge insulation were much less significant than the values without insulation in all the horizontal directions. In the northern direction, the temperature fluctuated most dramatically, e.g., on 12.02.2017 the daily temperature difference in the northern direction was 25.8 to 31.8 °C (6.0 °C difference) for the N-Module, and 26.1 to 48.1 °C (22.0 °C difference) for the F-Module. The temperature fluctuations in the western and eastern directions were slightly less significant. In the southern direction of both testing modules, the temperature fluctuation was the least, e.g., on 12.02.2017 the daily temperature difference in the southern direction was 23.7 to 24.9 °C (1.2 °C difference) for the N-Module, and 24.9 to 29.4 °C (4.5 °C difference) for the F-Module. It was obvious that the slab edge insulation boards had significant variations in effectiveness when they were installed in different sides of a slab. As an example, in an area with a comparatively high average annual temperature, where most of the cooling/heating energy is consumed in the summer, the most effective way to decrease heat transfer through the slab would be the installation of the slab edge insulation on the side corresponding to the direction of the source of the solar radiation.

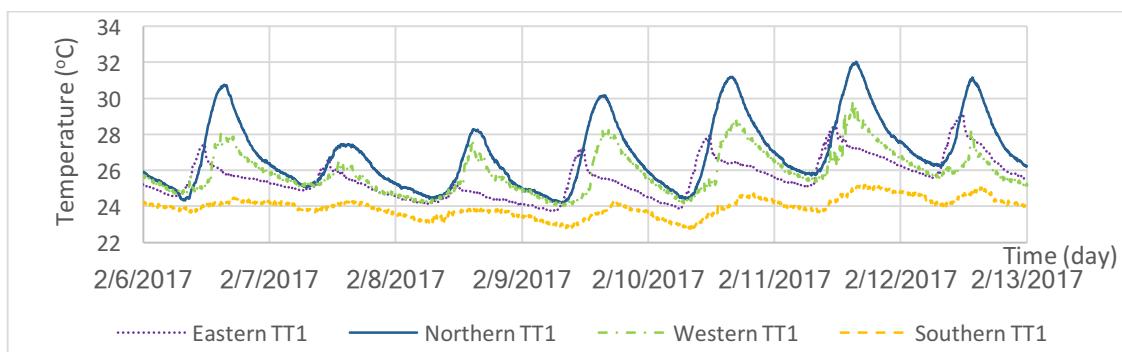


Figure 9. Temperature fluctuation at the four sides of the slab edge for the N-Module

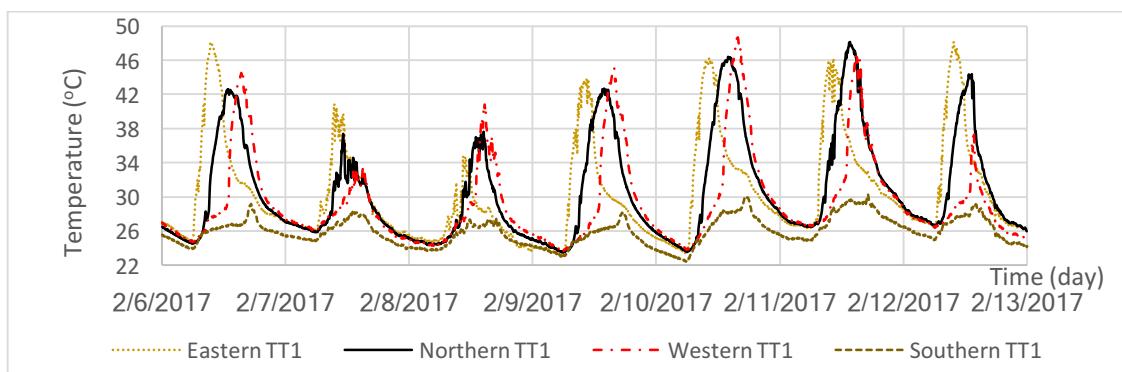


Figure 10. Temperature fluctuation at the four sides of the slab edge for the F-Module

## Numerical simulation results

A transient two-dimensional (2D) Finite Volume Method (FVM) model was developed for investigating the thermal effects of the slab edge insulation. Three-dimensional corner effects were ignored at this stage. The physical and dimensional parameters adopted were the same as the parameters in the experiments described above. The assumed boundary conditions are shown in Figure 11.

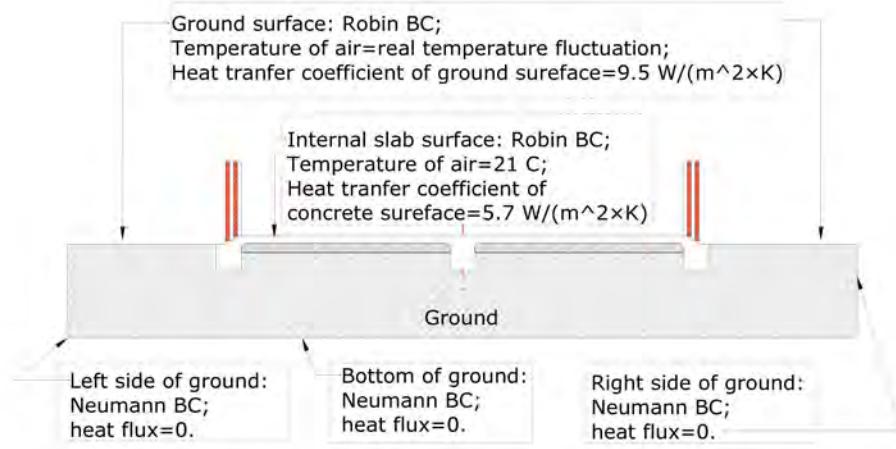
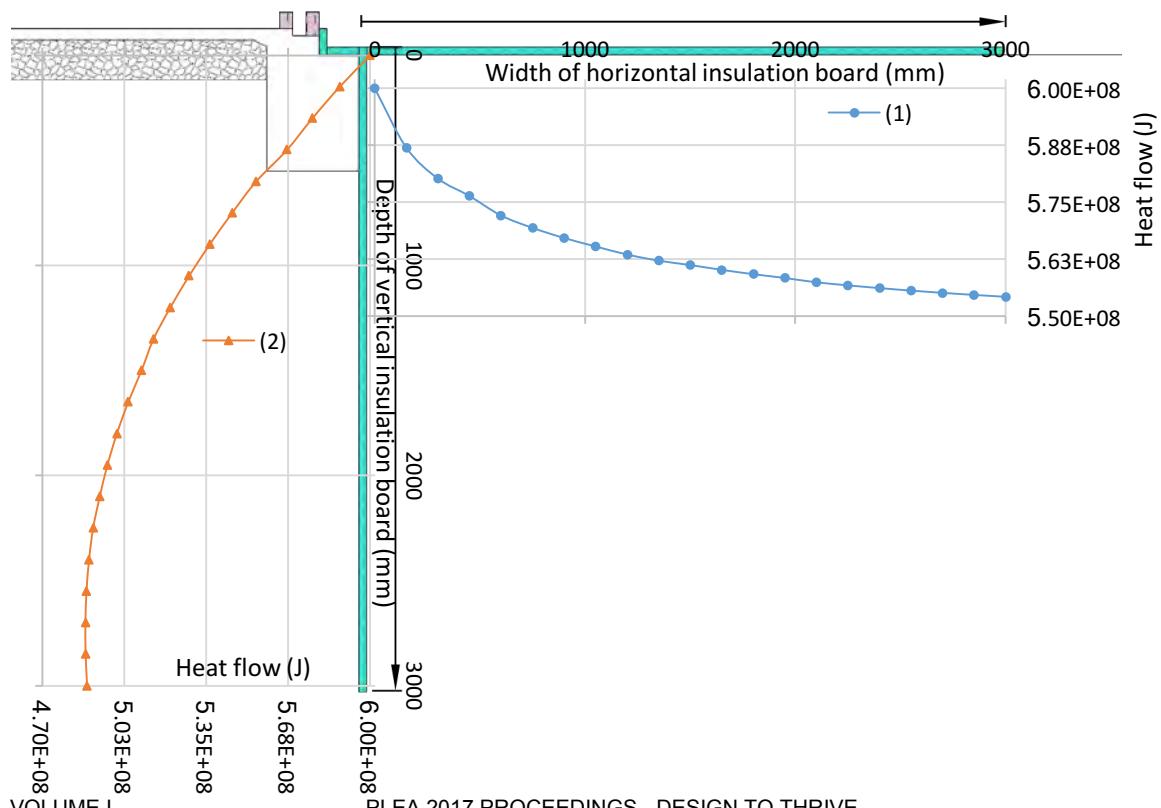


Figure 11. Section X-X and boundary conditions

Through the numerical simulation it was found that the installation of insulation around the slab edge provided better thermal performance compared to the use of insulation on the underside of the slab, either in the central area or under the complete underside. In addition, two other situations were simulated as shown in Figure 12:

- (1) The thickness of the horizontal insulation board (XPS3 in Figure 3) was fixed at 30mm while the width was varied from 0mm to 3000mm;
- (2) The thickness of the vertical insulation board (XPS2 in Figure 3) was fixed at 30mm while the depth was varied from 0mm to 3000mm.

Figure 12. Part Section X-X, and relationship between heat flow and dimension of insulation boards



The heat flow from the interior of the module through the surface of the slab to the ground beneath in situation (1) and situation (2) are shown in Figure 12. It can be seen that in both cases the heat flow decreased significantly as the length of the insulation board increased. Comparing the thermal effect of insulation in the horizontal and vertical direction, the vertical insulation board along the slab edge was more effective than the horizontal insulation on the ground surface.

## Conclusion

Through experimental and numerical analysis, it was shown that the installation of insulation around the external slab perimeter can effectively decrease heat flow through the slab, thus reducing the energy consumption in maintaining indoor thermal comfort. Compared with installing insulation on part or all of the underside of the slab, insulation around the slab edge provided better thermal performance. For the insulation boards of the same size, insulation board installed in the vertical direction was more effective than insulation board in the horizontal direction. The thermal efficiency of the slab edge insulation decreased markedly with insulation width in the horizontal direction and depth in the vertical direction. Optimum strategies for saving energy are needed to utilize slab edge insulation effectively and will be different for houses in different climates. The climate, the length and depth of insulation, and its position and location should all be considered. As an example, for a residential building in Newcastle, the suggested application of slab edge insulation would be to install vertical slab edge insulation board of 30mm (thickness) and 1500mm (depth) around the slab perimeter on the northern, eastern and western edges.

## References

- Hagentoft, C.E. (1988). *Heat loss to the ground from a building: slab on the ground and cellar*. Lunds Tekniska Högskola: Byggnadsfysik LTH.
- Neymark, J., Judkoff, R., Beausoleil-Morrison, I., Ben-Nakhi, A., Crowley, M., Deru, M., Henninger, R., Ribberink, H., Thornton, J., Wijsman, A. and Witte, M. (2008). *International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST): In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction*. USA: National Renewable Energy Laboratory.
- Page, A., Moghtaderi, B., Alterman, D. and Hands, S. (2011). *A study of the thermal performance of Australian housing/ NOVA*. Newcastle: The University of Newcastle.
- Shipp, P.H. (1982). Basement, crawlspace, and slab-on-grade thermal performance. In: *Proceedings of ASHRAE/DOE Conference on the Thermal Performance of Exterior Envelopes of Buildings*, Las Vegas, Nevada. 6-9 December.
- Statistics, A.E. (2016). *Australian Energy Update 2016*. <https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2016-australian-energy-statistics.pdf>



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Challenges for the integration of sustainable material use into dwelling design and construction

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**Abstract:** The environmental impact of building materials is gaining significance. However, architects face a number of challenges when trying to integrate sustainable material use in the design process. In this paper, the main challenges are listed based on lessons learned from the Flemish design and construction practice. A combination of research outcomes is used: 1) results from a large-scale survey on the architects' knowledge of environmental impact assessment (EIA), 2) semi-structured interviews with architects on the material selection process whilst designing and 3) semi-structured interviews on criteria for architect-friendliness of EIA tools. A survey with clients and interviews with contractors are used to include their point of view. Generally, it seems that architects have already come a long way on energy performance, but there is still much work on implementing sustainable material use in building design. Since there are no targets for the environmental impact of buildings (yet), there is a lack of awareness, knowledge and information on sustainable material use. Most architects have developed a pattern of habits for material choices, which does not include sustainability as a selection criterion. These identified challenges need to be overcome to achieve more sustainable material use in design and construction practice.

**Keywords:** Sustainable material use, architectural design process, design challenges, material choices

### Introduction

Up to now, the focus of sustainable building has mainly been on energy performance. Due to the strict EU energy performance targets, the operational energy use of buildings has already significantly improved over the last years and the relative share of the environmental impact caused by building materials has increased (Hollberg and Ruth, 2016, Passer et al, 2012). Therefore, the responsible use of resources and raw materials in building construction is gaining importance.

In Europe, initiatives such as the “Roadmap to Resource Efficient Europe” (European Commission, 2011) and the “Closing the loop” action plan on circular economy (European Commission, 2015) were launched over the last years, in which a Life Cycle Assessment (LCA) based environmental impact assessment (EIA) of building materials and construction is promoted. Hence, sustainability has to gain importance in the material selection process to further improve the buildings’ overall environmental performance.

In order to be effective, the integration of sustainable material use should become an inherent part of the design and construction process. In Flanders (Belgium), architects, clients and contractors are identified as the three main actors in the decision making process (Meex et al, 2016). However, these actors currently face a number of challenges when trying to implement sustainable material use in design and construction practice.

## Methods

This paper combines research outcomes from different empirical research steps that explore the role of the architect, client and contractor in the Flemish design and construction sector. The focus is on dwelling construction, which implies that mostly individual clients, small-scale contractors and architecture offices are questioned. For the perspective of the architect, three different series of research data are used: 1) results from a large-scale survey (N=364, 2014) on the architects' knowledge of EIA principles and tools, 2) semi-structured interviews (N=9, 2015) on the material selection process whilst designing and 3) semi-structured interviews (N=5, 2014) on criteria for architect-friendliness of EIA tools. For the clients, a survey (N=138, 2016) was conducted at a construction fair in Brussels (Batibouw). For the perspective of the contractor, findings from a series of structured interviews and a brief questionnaire (N=9, 2015), conducted in Flanders, are used (Claes and Smetsers, 2016).

## Results and discussion

The barriers found in this research are categorized into three main categories: 1) lack of awareness, 2) lack of knowledge on sustainable material use and assessment tools and 3) lack of legal requirements. The findings are discussed in more detail here below.

### Lack of awareness

Firstly, it is found that there is a lack of awareness regarding the environmental impact of buildings and the role of (sustainable) building materials. The large-scale survey showed that most architects (67%) are concerned with sustainability in their design practice (Figure 1 (left)), but that this concern is mainly related to energy efficiency measures such as insulation and compactness. This is confirmed by the interviews: most architects associated sustainable building with sufficient insulation, passive solar gains, compactness,... and less with material choices or other additional efforts to reduce the environmental impact of building design. Similarly, in the interviews with contractors, sustainability was found to be related mostly to the good practices of energy-related measures (e.g. airtight construction, no thermal bridges,...).

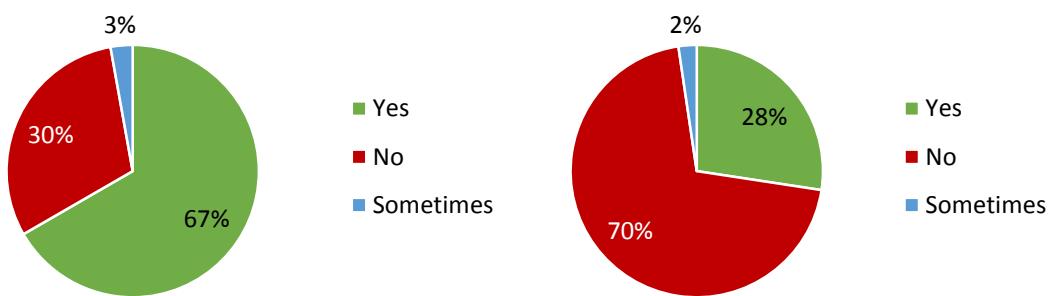


Figure 1. "Concerned with sustainability in design practice?" (left, N = 354) and "Additional efforts to reduce the environmental impact of building design, besides energy efficiency measures?" (right, N=343)

In the survey with architects, it was questioned whether respondents make additional efforts, besides energy efficiency measures, to reduce the environmental impact of building design (Figure 1, right). Only 28% of the respondents already tries to reduce the environmental impact of their designs. Of the 70% that does not (yet) deliver additional efforts, 44% indicates that they would be willing to do so, 7% would not be willing to do so

and for 49% it depends on the circumstances. Most frequently mentioned reasons for not making additional efforts relate to the additional work load, costs and time. Some architects who are willing to make additional efforts think it will become necessary in the future. However, they also indicate that they have too little knowledge on environmental impact and fear the additional costs. Respondents who indicated that it depends on the circumstances, also mostly mention the additional costs, the interest of the clients, the rate of return for the office and the additional work load and time investment. Similar barriers for moving towards more sustainable design and construction practices in general were also found in e.g. Häkkinen and Belloni (2011) and Pitt et al (2009).

Architects' drivers for material choices are mainly cost (79%), clients' wishes (75%), previous experience (73%), personal knowledge (68%) and aesthetics (68%); other and more sustainability related drivers (such as sustainable production process or recycled content of the materials) are less prominent (<30%). On the other hand, for clients' material selection, the look of the material and durability/low maintenance are the most important drivers (Figure 2). Factors such as technical quality and cost are also quite important, but the ecological footprint of the material is found to be the least important driver for material choices among clients. In general, the awareness of all actors in the design and construction process on the importance of sustainable material use seems limited and sustainability related aspects are the least decisive drivers for material choices in design and construction yet.

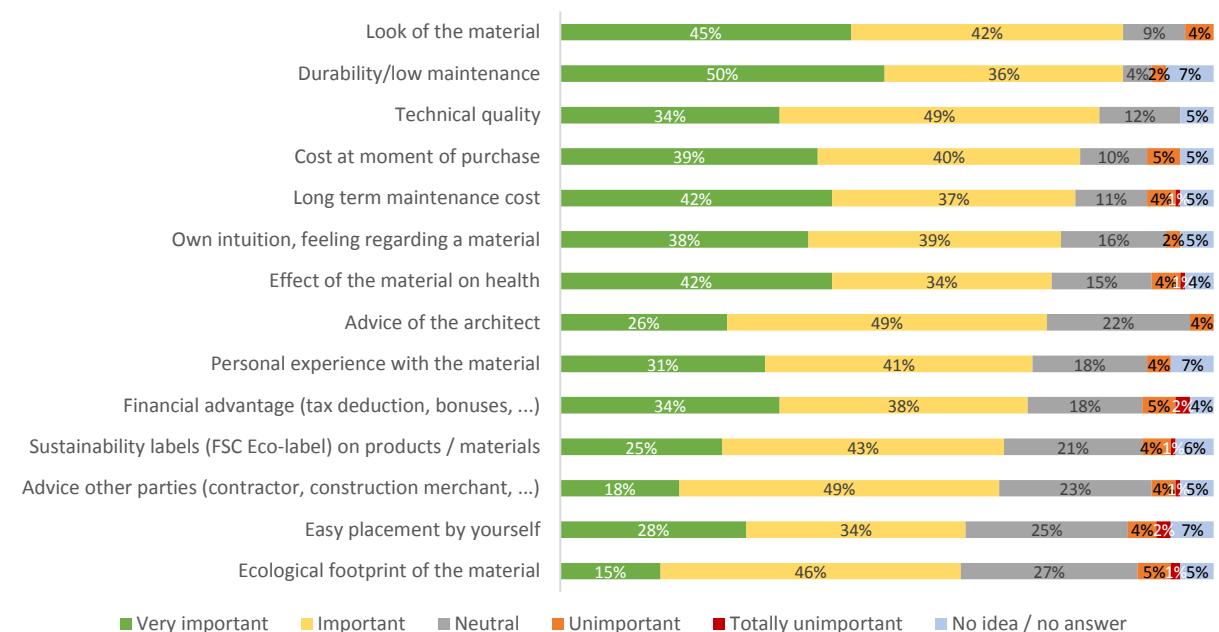


Figure 2. Clients' drivers for material choices and their importance (N=137)

### **Lack of knowledge on sustainable material use and assessment tools**

Throughout the research, it became clear that the interpretation of sustainable building and sustainable material use is rather subjective and mainly depends on personal beliefs of architects and contractors. When architects in the large-scale survey were asked what they associated with sustainable material use (Figure 3), the most frequent response was related to the materials' durability (71%), followed by the recyclability (54%) and the low environmental impact during e.g. the production process (53%). Among contractors,

durability was also most frequently selected, together with a material certificate/label (89%). However, it should be noted that the contractors also considered a general quality label (i.e. Belgian BENOR label) as a sustainability label. End-of-life recyclability (56%) was also associated with sustainable material use by contractors. For clients, the fact that a material requires little maintenance (85%) and/or is durable (79%) was found to be (very) important in order to be considered as sustainable, followed by its impact on health (63%). These results indicate that sustainable material use has a subjective interpretation and is still related more to a material's durability than to other ecological aspects.

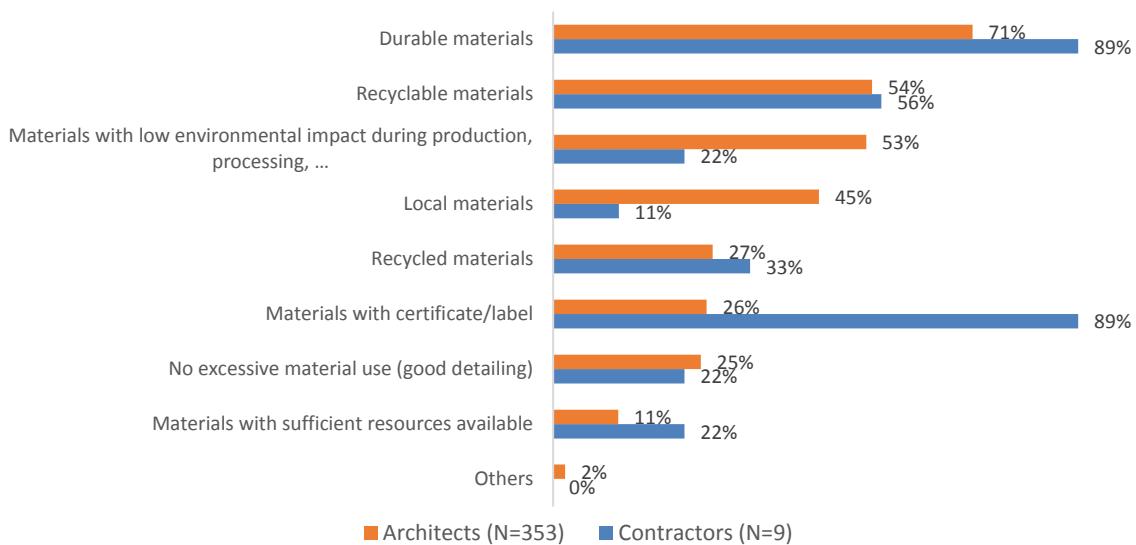


Figure 3. Interpretations of sustainable material use by architects (N=353) and contractors (N=9)

This subjective interpretation is linked to the lack of (general) knowledge on sustainable material use. LCA is widely recognized as a scientific method to evaluate the environmental impact of materials and products. Although several LCA-based environmental impact assessment tools have already been developed, it was found in the large-scale survey that architects have little knowledge on EIA methods and tools. For instance, only 42% has heard of the LCA method and only 15% heard of an Environmental Product Declaration (EPD). Also among the contractors, the knowledge of LCA and EPD was found to be quite limited: only 33% has heard of LCA and 11% of EPD.

The familiarity of the architects with LCA-based databases and EIA tools was also quite limited (Figure 4). Global sustainability assessment tools (e.g. BREEAM) were quite well-known and used to some extent. Considering LCA-based databases and EIA tools, only the Dutch NIBE classification (NIBE, 2016) was quite well-known and used to a certain extent by the architects. The NIBE classification was also mentioned by a small number of architects and contractors in the semi-structured interviews as one of the few aids that they are familiar with when integrating sustainable material use. However, the reliability of this classification system was often questioned by the respondents, as classifications changed over time (probably due to changes in the impact assessment methodology). Similar results were found in a survey by Olinzock et al (2015): they uncovered that the expertise level of building practitioners on LCA is often limited and that LCA-based software tools are currently rarely used beyond research purposes. Also by Means and Guggemos (2015 pp. 802), similar findings were done: "LCA tools and databases generally require a completely separate activity, data input and expertise; they are not integrated into routinely used architecture, engineering and construction (AEC) tools, methods or best practices".



■ Never heard of it   ■ Heard of it, but never used it   ■ Heard of it and used it (limited)   ■ Heard of it and used on a regular basis

Figure 4. Architects' familiarity with LCA-based databases and EIA methods and tools (N=330)

In addition, it was uncovered that both architects and contractors consider it hard to find reliable, objective information regarding the environmental impact of construction materials and products. Since architects and contractors have a large responsibility in the quality of the design and construction of a dwelling, they are not eager to deviate from their usual choices of mainstream or conventional products. These conventional products have already proven their value over the years, whereas newer, more alternative products often still lack these references and proof of quality or (added) value over a longer period and therefore present a greater risk. Some contractors (and some architects) also declare to mistrust environmental product information due to assumed lobbying practices from the material producers, which could influence the objectivity and reliability of the environmental product information. In addition, contractors often think that the integration of sustainable material use is more a responsibility of architects and material producers.

Nevertheless, the majority of architects (54%) indicates that they would use a tool to assess the environmental impact on a voluntary basis. 40% of the architects would not do this and 6% was in doubt and answered sometimes (Figure 5). Most mentioned reasons for not using such a tool are related to the additional work load and time investment, lack of knowledge, lack of interest of client and the lack of legal requirements. Additionally, some architects do not think this fits within their work package.

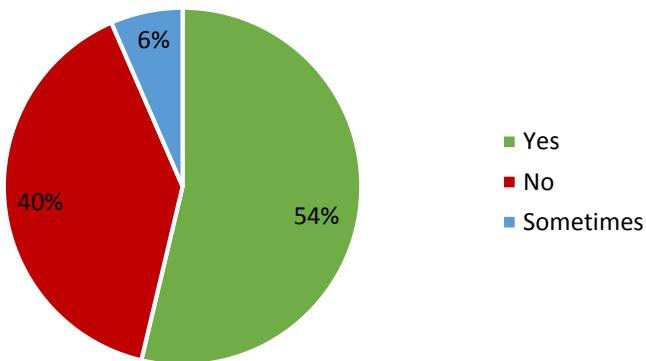


Figure 5. "Would you use a tool for the environmental impact assessment on a voluntary basis?" (N = 337)

This unwillingness to use an environmental impact assessment tool on a voluntary basis, in combination with the low familiarity with the existing LCA-based environmental impact assessment tools and limited knowledge on EIA, could indicate that there is a need for a user-friendly tool, oriented to architects, which enables them to perform such an environmental impact assessment of their design solutions.

#### ***Lack of legal requirements***

At this moment, in absence of legal requirements or targets for the environmental impact, most architects (and contractors) miss a valuable argument to convince clients. According to the interviewed architects and contractors, regulations and/or policy incentives are needed to introduce a shift towards more sustainable selection motives for materials. This would encourage the uptake of sustainable material use: "The sustainable evolution will happen but it has to be imposed by the government, because for clients only cost matters". Especially cost was found to be an important barrier for clients to choose sustainable materials, at least according to the architects and contractors. For instance, one architect states that "it depends on the client, if he says that he has a budget to insulate his roof with flax or a bio-ecological material then it is possible [...]" And a contractor claims that "I always choose the most sustainable material, but when this is three times as expensive, than the client will never pay this. The client is willing to pay a little bit more when a product is sustainable".

Although the "willingness to pay more for sustainable materials" is seriously doubted by architects and contractors in the interviews, the survey among clients shows that the majority (84%) is willing to pay more for more sustainable materials (Figure 6): 21% is willing to pay 1-5% more, 43% is willing to pay 6-10% more and 20% of the clients is even prepared to pay more than 10% more than for conventional materials. However, when the additional cost approaches 25% or more the willingness significantly decreases.

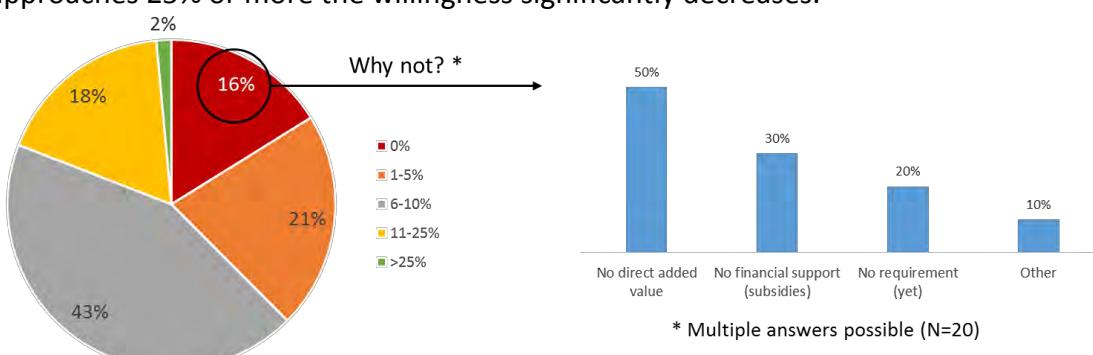


Figure 6. "How much are clients willing to pay more for a more sustainable material (N=136)? If 0%, why?"

This willingness to pay more for sustainable building materials is similar to tendencies found in marketing research regarding other green consumer products (e.g. Miremadi et al, 2012). The limited share of clients who are not willing to pay more (16%) mainly do not see the added value (50%) and/or lack financial support (30%) or legal requirements (20%). Further research is needed to determine how much clients are willing to pay more in case of real material choices.

Nevertheless, according to Pitt et al (2009), architects have an educating role towards the client, who is a principal stakeholder in determining the sustainability level of a construction project. Similar to sustainable building in general, there is still room for improvement on the knowledge level and communication of information regarding sustainable material use in the design and construction practice. Imposing requirements could support and/or accelerate this process.

However, implementing legal requirements for the environmental impact of buildings would influence the design practice. Therefore, the architects (in the large-scale survey) were asked to specify their attitude towards a future obligation to assess the environmental impact of building design in two situations: 1) without a mandatory benchmark to comply with and 2) with a mandatory benchmark. In case no mandatory benchmark is imposed (Figure 7, left), most respondents have a neutral attitude, which is also slightly skewed towards the reluctant side. In case a mandatory benchmark is imposed (Figure 7, right), the architect's attitude clearly shifts more to the reluctant side. Most commonly given explanations on the reluctant side are the additional cost, extra work load and the overregulation limiting the architectural freedom. Nevertheless, these respondents also mention that an obligation without mandatory benchmark would have little to no effect. Architects on the enthusiastic side almost all state that it is about time to take environmental impacts into account. According to these respondents, an assessment obligation without mandatory benchmark would have a sensitizing effect and it would be a valuable argument towards clients. However, in case a mandatory benchmark is imposed, even these architects fear the additional cost and work load.

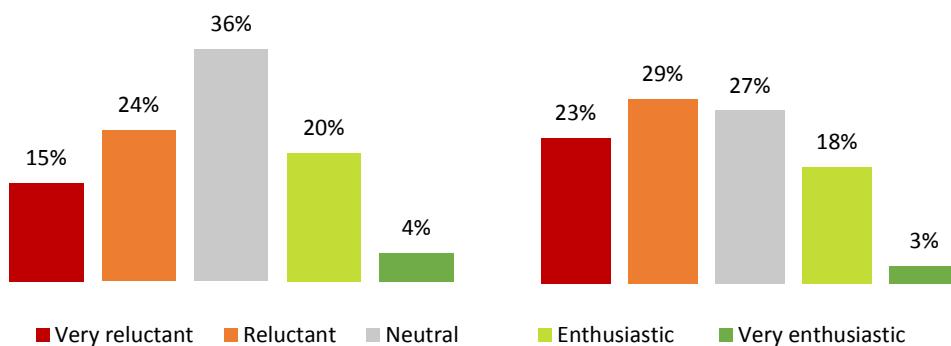


Figure 7. The attitude of the architects towards a future obligation to assess the environmental impact without (left, N=338) and with (right, N=328) mandatory benchmark

## Conclusions

This paper discusses the challenges for the design and construction sector when moving towards more sustainable material use. In general, it can be concluded that most architects, clients and contractors lack awareness and knowledge on sustainable material use and environmental impact assessment. Currently, sustainable building is still mainly associated with achieving good energy-efficiency performances by means of passive design solutions,

insulation, etc. It is found that the majority of architects and contractors do not really make additional efforts to integrate sustainable material use in their design and construction practices yet: the application of conventional materials is part of standard practice and a pattern of habits. In addition, architects and contractors declare that, without regulation or obligation, they often lack a valuable argument towards the client. Financial incentives and subsidies could stimulate the uptake of sustainable material use, according to clients. Nowadays, clients simply wish to meet the requirements and are mainly concerned with the cost and timing of a design project, which makes it hard for architects to gain experience with and knowledge on sustainable material use in the context of a design project. However, implementing such regulations would also influence the design and construction practice and architects mostly fear the additional costs, extra work load and a limitation of their architectural freedom. These findings also indicate the need for the availability of a user-friendly environmental impact assessment tool. In conclusion, to move towards more sustainable material use in practice, the general awareness regarding the importance of sustainable material use and the knowledge level and availability of usable tools will have to increase and legal requirements on sustainable material use will have to be implemented.

## Acknowledgements

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## References

- Claes, N. & Smetsers, J. 2016. *Rol van de aannemer bij de materiaalkeuze tijdens de bouw van eengezinswoningen* (in Dutch). Master thesis, Hasselt University & KU Leuven.
- European Commission (2011). Roadmap to a Resource Efficient Europe. COM (2011) 571. Brussels.
- European Commission (2015). Closing the loop - an EU action plan for the circular economy. COM (2015) 614. Brussels.
- Häkkinen, T. & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information*, 39, pp. 239-255.
- Hollberg, A. & Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment*, 21, pp. 943-960.
- Means, P. & Guggemos, A. (2015). Framework for Life Cycle Assessment (LCA) Based Environmental Decision Making During the Conceptual Design Phase for Commercial Buildings. *Procedia Engineering*, 118, pp. 802-812.
- Meex, E., Knapen, E. & Verbeeck, G. (2016). Case study analysis of the material selection process during dwelling design in Flanders. In: Železná, J., Hájek, P., Tywoniak, J., Lupíšek, A. & Sojková, K., eds. *YRSB16 - iiSBE Forum of Young Researchers in Sustainable Building 2016*, 2016 Prague, Czech Republic. Czech Technical University in Prague, pp. 240-249.
- Miremadi, M., Musso, C. & Weihe, U. (2012). *How much will consumers pay to go green?* [Online]. Available from: <http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/how-much-will-consumers-pay-to-go-green> [Accessed March 6 2017].
- Nibe. (2016). *Hoe duurzaam zijn bouwproducten?* (in Dutch) [Online]. Available from: <http://www.nibe.info/nl/milieuclassificaties> [Accessed November 16 2016].
- Olinzock, M. A., Landis, A. E., Saunders, C. L., Collinge, W. O., Jones, A. K., Schaefer, L. A. & Bilec, M. M. (2015). Life cycle assessment use in the North American building community: summary of findings from a 2011/2012 survey. *The International Journal of Life Cycle Assessment*, 20, pp. 318-331.
- Passer, A., Kreiner, H. & Maydl, P. (2012). Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings. *The International Journal of Life Cycle Assessment*, 17, pp. 1116-1130.
- Pitt, M., Tucker, M., Riley, M. & Longden, J. (2009). Towards sustainable construction: promotion and best practices. *Construction Innovation*, 9, pp. 201-224.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Zooming in on Biomimicry: The Potential of Tensegrity Structures

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**Abstract:** The foundations of biomimicry lie with the idea that Nature can inspire solutions to complex human problems. Biomimicry in Architecture is a rapidly growing field which also echoes the new paradigm of a circular economy. Recent applications of biomimicry in architecture have shown that it is possible to achieve factor 100 savings in resource and energy use. Tensegrity structures are one of the many aspects of biomimicry, and research has made a lot of progress on the theoretical foundations of tensegrity structures. Yet, the construction remains one of the biggest challenges and as a consequence most of these structures only exist as prototypes. This paper presents findings of a project aimed at facilitating industrial manufacturing and endless replications of tensegrity components. The results on the joints and hinges, as well as the prototype that was built to show how the practical application works, allow to exploit the benefits tensegrity has to offer to architects in terms of lighter structures which require significantly less material and energy.

**Keywords:** biomimicry, tensegrity, building structures, façade design, biomimetic.

### Introduction and background

The foundations of biomimicry lie with the idea that Nature has undergone a fine-tuning of its evolutionary mechanisms for billions of years and can therefore represent a resourceful inspiration to solve complex human problems. Biomimicry in Architecture is a rapidly growing field which also echoes quite harmoniously the new paradigm of a circular economy. Recent applications of biomimicry in architecture have shown that it is possible to achieve factor 100, if not 1000, savings in resource and energy use (Pawlyn, 2011).

Tensegrity structures are one of the many aspects of biomimicry. However, whilst in most cases we discover things in Nature that can then be transferred on to architecture, for tensegrity the opposite is true. It was first theorised by humans and only afterwards it was found that it may represent the theoretical basis for some underlying principles of cells behaviour and mechanism. Put simply, one of the most widely agreed upon definitions of tensegrity structures defines them as a system which is capable of self-equilibrium and is composed by a series of compressed components surrounded by a continuum of tensioned components.

Research on the theory behind tensegrity has progressed well since the concept was first theorised. Such research has revolved around form-finding for tensegrity structures (Tran and Lee, 2010, Li et al., 2010, Kohestani, 2012, Tibert and Pellegrino, 2011), multi-level structures (Nagase et al., 2016), structure deployment (Sultan and Skelton, 2003), geometric and non-linear analysis (Tran and Lee, 2011), and configuration and stability (Zhang et al., 2009)

## Relationship with Nature

Fuller (1969) noted that men used what he defines the “inefficient pressure” when thinking about constructions. Fuller uses the example of laying stones over stones to create dwellings, for terrestrial constructions. However, he also reflects that for boats, structural rigidity (e.g. masts) is obtained through tension and not compression (Fuller, 1969). Similarly, Nature uses continuously tension and only discontinuously and in an isolated manner compression (Fuller, 1969 p.242). Tensegrity can also be understood through the analogy with weaving. Weaving creates cells and these cells can be further combined into 2D and 3D final products. Examples can be seen in Figure 1 and Figure 2.

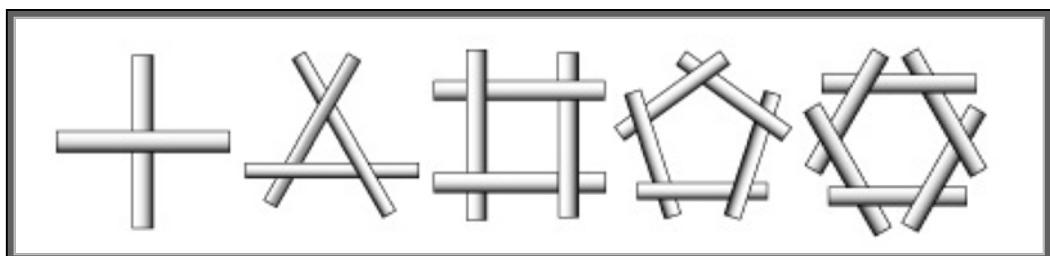


Figure 1 - Basic unitary cells to create twines



Figure 2 - Plaited wicker ball with triangular, pentagonal and hexagonal outlines

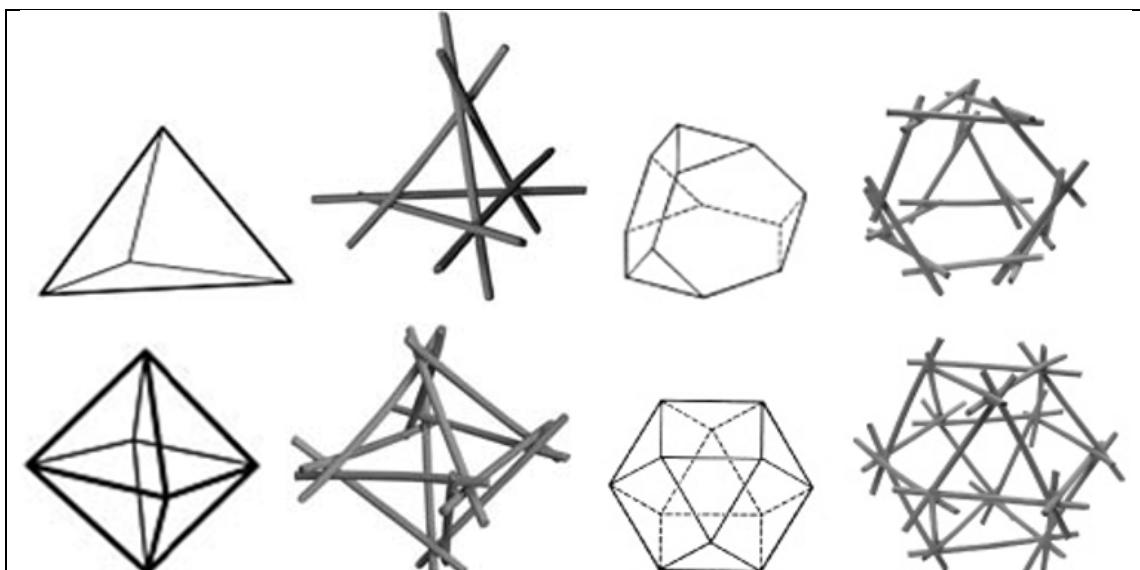


Figure 3 - Regular polyhedrons and their helicoidal equivalents

The cells shown so far are limited to polygons. However, it is also possible to translate 3D solids (e.g. tetrahedron, octahedron etc.) into systems of woven cells by way of small shafts, thus creating hybrid configurations that are called helicoidal polyhedrons (Figure 3). These are the starting points to develop the equivalent tensegrity structures; one example for the helicoidal tetrahedron can be seen in Figure 4.



Figure 4 - Helicoidal tetrahedron and its equivalent tensegrity

The twined cell has therefore become an endo-skeletal structure like in animals where muscles are external to the bones. A full discussion of tensegrity structures would take more space than this paper allows. However, the main point is that these structures can show a high mechanical resistance and a lower use of material but their calculation can be very complex and incorrect because tensegrities are a particular phenomenon, both geometrically and structurally (Grip, 1992). Tensegrity structures and structural principles have been identified in astronomy, atomic physics and mechanics (Kurtz, 1968), biology (Ingber, 1997, Ingber, 1998, Wang et al., 2001, Ingber, 2003), inorganic chemistry (Tsu et al., 2003), anatomy (Gómez Jáuregui, 2004), and biomechanics (Caluwaerts et al., 2013).

### **Structural Unity and Versatility of Use**

Tensegrity structures, if well designed, allow for lightness, easy transportation and assembly, and multiple potential applications in architecture and engineering. Emmerich (1996) is one of the fathers of tensegrity structures, and he observed that structural problems related to architectural design consist of five hierarchically-ordered stages: (1) ideation, (2) dimensioning, (3) stabilisation, (4) calculus, and (5) construction. For tensegrity structures, the first four have been widely investigated but the fifth remains in its infancy and few examples exist of the application of tensegrity in real-world structures (Gómez Jáuregui, 2004). The questions that remain open to address the fifth stage are:

- How can a tensegrity structure be tensioned with the guarantee that the tension will be permanent?
- What should the joints be like to be industrially manufactured at scale?
- Which construction methods should be used given (a) the geometrical complexity of the system and (b) their lack of rigidity before the whole structure is tensioned?

This paper aims to contribute to answering these questions. The project design and the results are shown in the next sections.

## The Project Design

The critical element of a tensegrity structure is the design of the joint. Many joint solutions exist, such as the Vestrut system (Quaglia, 2010), the KK system (MERO, 2017), and the pioneering Nodus system (British Steel Corporation, 1976). All these systems represent, structurally speaking, joints. This means that in the calculus both bending moments and shear forces, that could occur due to loads, have to be considered for the struts. Therefore, the idea has been to design a joint that from a static and technological point of view would represent a perfect hinge. This is done to limit loads on the struts solely to the normal stress. If successful, the design of such perfect hinge would allow the (either tensioned or compressed) strut to rotate freely in any direction, including that of its own axis. Additionally, such a system would possess the characteristics of universality and versatility that successful structural systems have.

## Results

The joint was therefore designed as a group of components that are assembled without any welding. The components are:

- A central linchpin
- Two symmetric central elements
- Two further symmetric elements (on the top of the two symmetric central elements)
- 'Lids', conceived to allow attachment to sub-structures (e.g. further struts or panelling systems)

The system is hold together through a single bolt for the central elements and four screws for the lids. The final form is that of a sphere with three runners (gliding mechanisms) around its vertical axis (Figure 5). These runners host the smaller spheres connected to ties and struts (which we will call strut-spheres and tie-spheres) to allow rotation and reduce the contact surface in order to minimise friction.

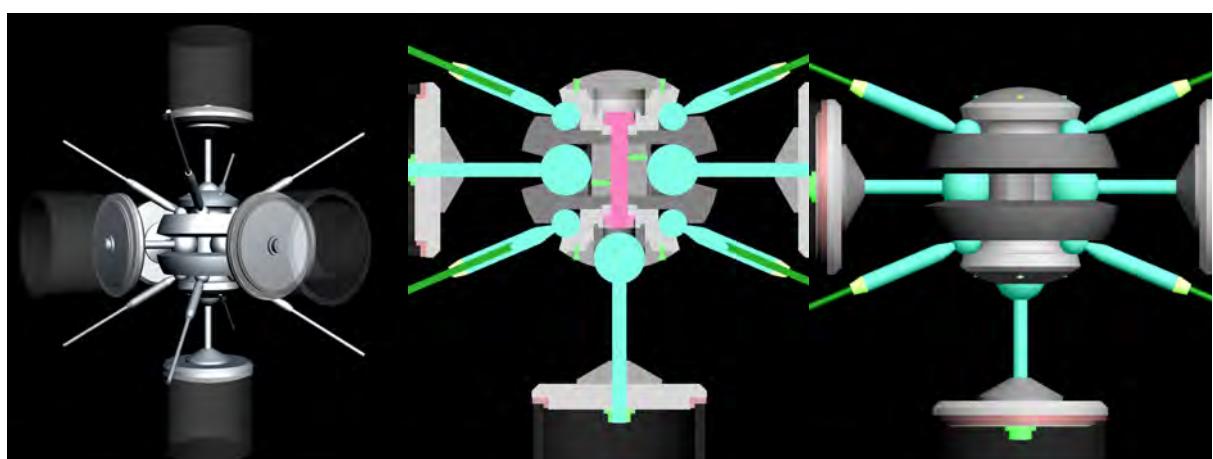


Figure 5 - Three different views of the 'perfect hinge' designed as a joint for tensegrity structures

Both strut-spheres and tie-spheres have a right-hand thread on one side and a left-hand on the other to allow for structural adjustments as well as the fine-tuning of the structure. Once the structure has been assembled, all ties and struts are free to rotate in space without altering the tensions within the tensegrity structure.

With the joint designed, the outstanding task was to embed it in a system that would enable light and resistant structures, continuously tensioned and discontinuously compressed, that would meet those requirements of universality and versatility of successful structural systems. Glass is an ideal material when compression loads are involved and steel is equally ideal for tensioned elements. For this reason, the proposed tensegrity structure is a structural module that employs steel cables and glass tubes.

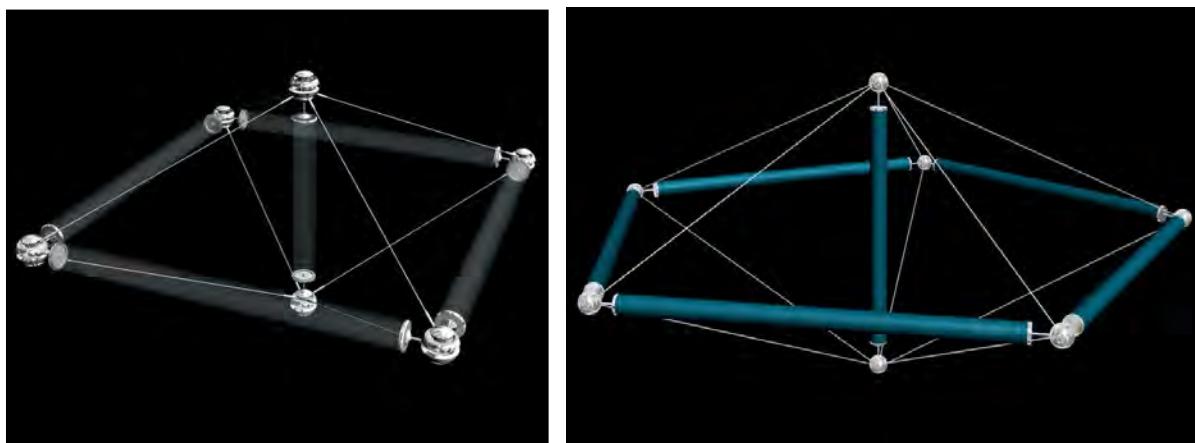


Figure 6 - Two examples of the tensegrity structure proposed with glass tubes and a perfect hinge as a joint – the image on the left shows an analogy with a bicycle wheel

Starting from the designed model, a real model was built as a prototype for testing. The characteristics of the model are given in Table 1. These elements produce an octahedron module similar to the one shown in the left-hand side of Figure 6.

Table 1 - Details of the essential elements for the octahedral tensegrity structure

<b>Element</b>	<b>Quantity</b>	<b>Details</b>
Outside glass tube	4	L=420mm, $\phi = 35$ mm, $s = 1.5$ mm
Inner glass tube	1	L=231mm, $\phi = 35$ mm, $s = 1.5$ mm
Steel ties	8	L=355mm, $\phi = 5$ mm
Perfect hinge	6	$\phi = 46$ mm

The module was tested in SAP to establish the value for the extension of the central strut to tension and stabilise the whole system. It was found that for each unscrewed mm of the thread in the strut-sphere: ties were tensioned by  $Q_t = +107.37$  kg, central strut was compressed by  $Q_c = -176.34$  kg, and outer struts were compressed by  $Q_c = -138.46$  kg. Figure 7 shows the results of the analysis.

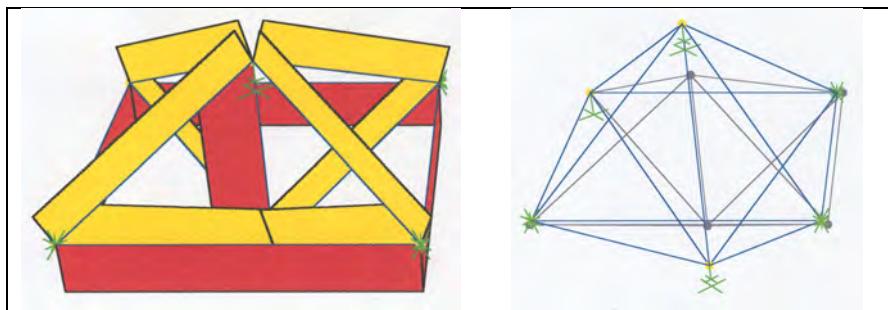


Figure 7 - Tensions (yellow) and Compression (red) diagrams [left] and Deformation diagram [right]

Images of the real prototype that was realised and assembled after design and calculations are shown in Figure 8.

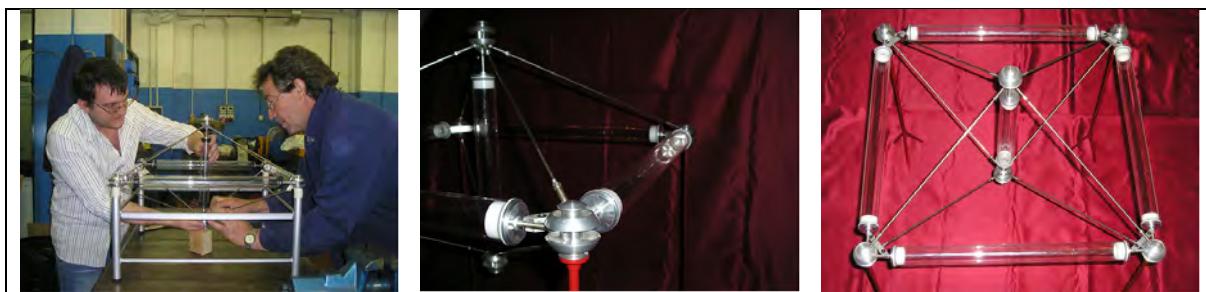


Figure 8 - Assembly and final look of the octahedral tensegrity structure with perfect hinges as joints

Once the system had been tested and proved to work, truly endless combinations could be created from its flexibility and versatility.

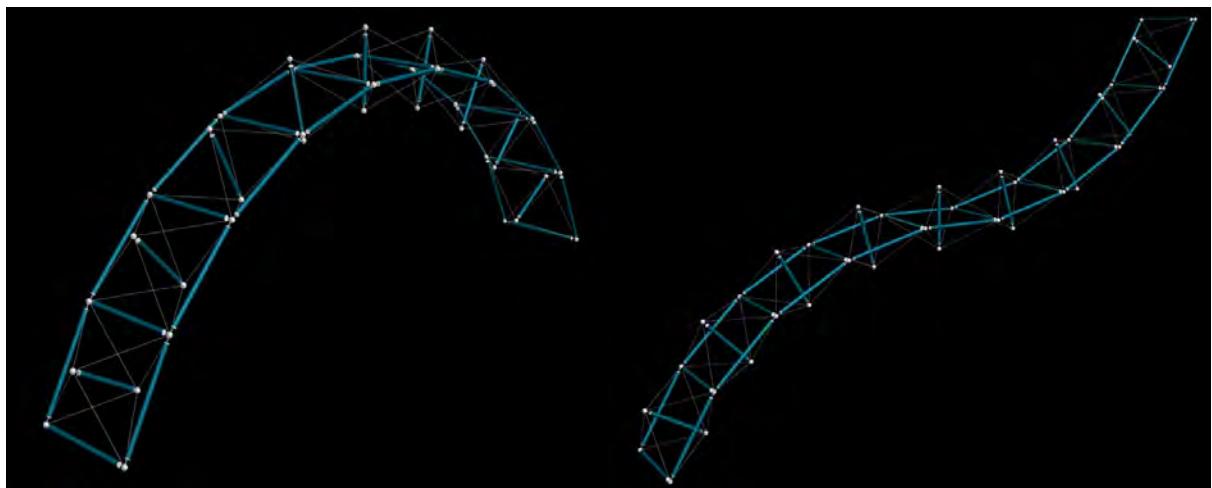


Figure 9 - Examples of tensegrity (predominant vertical direction)

Figure 9 shows two such examples where the models have been created with a predominant vertical direction to create elements such as arches, gridshells, and similar. Figure 10 instead shows two examples where the models were primarily developed in the horizontal direction, and that could be used with due adjustments in common building projects.

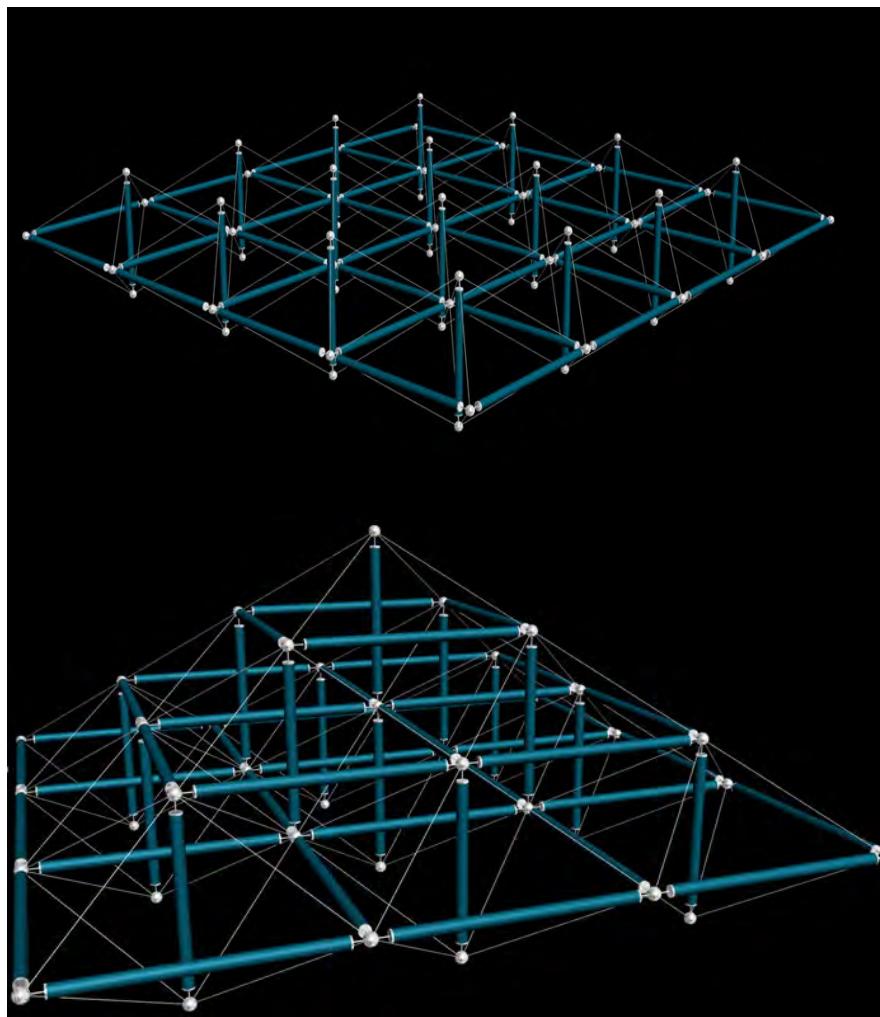


Figure 10 - Examples of tensegrity (predominant horizontal direction)

## Conclusions

This paper has presented findings from an ongoing research project aimed at facilitating industrial manufacturing and endless replications of tensegrity components in order to facilitate its wider use. The results have presented a perfect hinge to be used as a joint, as well as the prototype that was built to show the practical application of our work. Our findings contribute to demonstrating the technical feasibility of tensegrity structures – what has so far been perhaps the main impediment to a wider adoption of these structures. The findings also contribute to the growing debate in the field and allow to practically exploit the benefits tensegrity has to offer to architects in terms of lighter structures which require significantly less material and energy. The joint has been patented in Italy and further work will aim at broadening the potential of its application. We would welcome collaboration for future research and development endeavours.

## References

- BRITISH STEEL CORPORATION 1976. *Nodus. Space Frame Grids Part 1: Design and Construction*, British Steel Corporation. Tubes Division.
- CALUWAERTS, K., D'HAENE, M., VERSTRAETEN, D. & SCHRAUWEN, B. 2013. Locomotion without a brain: physical reservoir computing in tensegrity structures. *Artificial life*, 19, 35-66.

- EMMERICH, D. G. 1996. Emmerich on self-tensioning structures. *International Journal of Space Structures*, 11, 29-36.
- FULLER, R. B. 1969. Design science, an economic success of all humanity. *Zodiac*, 58.
- GÓMEZ JÁUREGUI, V. 2004. *Tensegrity Structures and their Application to Architecture*. MSc Thesis, Queen's University Belfast.
- GRIP, R. 1992. The Correspondence Between Convex Polyhedra and Tensegrity Systems: A Classification System. *International Journal of Space Structures*, 7, 115-125.
- INGBER, D. E. 1997. Tensegrity: the architectural basis of cellular mechanotransduction. *Annual review of physiology*, 59, 575-599.
- INGBER, D. E. 1998. The Architecture of Life. *Scientific American Magazine*. January 1998.
- INGBER, D. E. 2003. Tensegrity I. Cell structure and hierarchical systems biology. *Journal of cell science*, 116, 1157-1173.
- KOOHESTANI, K. 2012. Form-finding of tensegrity structures via genetic algorithm. *International Journal of Solids and Structures*, 49, 739-747.
- KURTZ, S. A. 1968. Kenneth Snelson: The Elegant Solution. *Art News*. October 1968.
- LI, Y., FENG, X.-Q., CAO, Y.-P. & GAO, H. 2010. A Monte Carlo form-finding method for large scale regular and irregular tensegrity structures. *International Journal of Solids and Structures*, 47, 1888-1898.
- MERO. 2017. KK-Ball Node System - Available at: <http://www.mero-tsk.de/index.php/en/construction-systems/nodes/kk-ball-node-system-en> [Online]. [Accessed 17 January].
- NAGASE, K., YAMASHITA, T. & KAWABATA, N. 2016. On a connectivity matrix formula for tensegrity prism plates. *Mechanics Research Communications*, 77, 29-43.
- PAWLYN, M. 2011. *Biomimicry in architecture*, London, Riba Publishing.
- QUAGLIA, E. 2010. *Strutture reticolari spaziali con più ordini di gerarchia* [in Italian] - Available at: <http://webthesis.biblio.polito.it/2001/>. MSc Thesis, Politecnico di Torino.
- SULTAN, C. & SKELTON, R. 2003. Deployment of tensegrity structures. *International Journal of Solids and Structures*, 40, 4637-4657.
- TIBERT, A. & PELLEGRINO, S. 2011. Review of form-finding methods for tensegrity structures. *International Journal of Space Structures*, 26, 241-255.
- TRAN, H. C. & LEE, J. 2010. Advanced form-finding of tensegrity structures. *Computers & structures*, 88, 237-246.
- TRAN, H. C. & LEE, J. 2011. Geometric and material nonlinear analysis of tensegrity structures. *Acta Mechanica Sinica*, 27, 938-949.
- TSU, D. V., CHAO, B. S. & JONES, S. J. 2003. Intermediate order in tetrahedrally coordinated silicon: evidence for chainlike objects. *Solar energy materials and solar cells*, 78, 115-141.
- WANG, N., NARUSE, K., STAMENOVIC, D., FREDBERG, J. J., MIJAILOVICH, S. M., TOLIĆ-NØRRELYKKE, I. M., POLTE, T., MANNIX, R. & INGBER, D. E. 2001. Mechanical behavior in living cells consistent with the tensegrity model. *Proceedings of the National Academy of Sciences*, 98, 7765-7770.
- ZHANG, J., GUEST, S. & OHSAKI, M. 2009. Symmetric prismatic tensegrity structures: Part I. Configuration and stability. *International Journal of Solids and Structures*, 46, 1-14.



# PLEA 2017 EDINBURGH

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## **Microcity, an Innovative Building Integrating Sustainability Issues from Urban Design to Constructive Detail**

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**Abstract:** The Microcity building, which houses the new branch of the EPFL in Neuchâtel (Switzerland), is the result of a synergy-generating strategy based on partnerships, experimentation with innovative processes and the continuous integration of sustainability-related challenges. Ranging from urban design to construction details, this approach has integrated diversified notions such as institutional synergy, technological innovation, urban densification and high environmental quality. Through urban densification in the vicinity of public transport stops, this realization has played an essential role in stimulating the revitalisation of the entire neighbourhood (new public spaces and soft mobility facilities). At the building level, the strategy is based on solutions that focus on rational resource use and minimize environmental impacts (compactness, thermal quality of the building shell, natural light enhancement, high-performance electrical devices, and materials with favourable LCA). A large part of the structure is based on a hybrid, prefabricated system (wood and concrete), which allows a reduction of embodied energy and provides a high level of flexibility for future adaptations. Microcity is also a driving force for integrating renewable energies going beyond its own limits (photovoltaic centre on the roof and underground canal ring that uses water from the lake to reduce the impact of cooling).

**Keywords:** sustainable architecture, prefabricated construction, renewable energy, free cooling

### **Introduction**

Public institutions set a strong example for sustainability with their specific programme and emblematic status and can generate a driving force that goes far beyond their own spatial limitations. In this respect, the development of Microcity in Neuchâtel, Switzerland, reflects the huge potential of innovative moves like these ranging from its territorial strategy to the smallest construction details. Its conception owes a lot to the joint determination of local authorities and the EPFL to develop a skills hub for micro- and nanotechnology. This partnership ties in with the university's expanding network strategy, which aims to strengthen its presence throughout French-speaking Switzerland with the creation four new branches to generate innovative dynamics.

### **Urban integration and high-quality public areas**

Criteria for choosing the site for the EPFL's Neuchâtel branch were mainly the availability of land reserves in urban areas and the desire to optimize proximity with strategic actors in the field of microtechnology. The building programme also integrates spaces for Neode, the

science and technology research park promoting the creation of start-ups. Bearing in mind the stakes in terms of image for the region, the undertaking was not restricted to constructing an emblematic building to house the new centre of excellence but was also committed to overall neighbourhood redevelopment based on a masterplan with generous emphasis on public areas.

Another important feature of the process set in motion for development of this project was undoubtedly the special attention paid to interactive and iterative approaches. A working group was formed with representatives of the project supervisor, the City of Neuchâtel and both chairpersons of the two neighbourhood associations. Local inhabitants were thus able to follow the progress of the masterplan, express their concerns, expectations and preferences and influence the definition of certain planning measures. These iterative and interactive approaches ensured that the masterplan and general architectural project were well accepted by the population as a whole, as well as contributing to crucial coherence between the new complex and urban planning; indeed, Microcity has stimulated redevelopment of the surrounding public spaces by the City of Neuchâtel authorities. Street landscaping, linked with various traffic-calming mechanisms (a meeting area and a 30 km/hr restricted zone), ensures smooth cohabitation of all public sector functions and gives the entire perimeter a homogenous identity. In this context, public space is not just a mere extension of the architectural project but combines with the new building to form a strong identity serving the users of the site, the inhabitants of the neighbourhood as well as enhancing the international aura of the city and Canton (Van der Poel, 2014). In addition, several facilities connected with sustainable mobility are available for users such as a self-service bike station (Velospot), car-sharing (Mobility) and an electric-car-sharing station (ElectricEasy).



Figure 1. Site plan and public spaces in the surroundings of Microcity (Document: City of Neuchâtel, Department of Urban Planning).



Figure 2. Insertion of the building into the urban fabric (Picture: Yves André).

### **Conceptual interweaving and constructive hybridization**

The building's strategic position contributes to the urban densification process by creating new hubs in the immediate vicinity of public transport stops. It makes sense in the urban layout as a meaningful polarity. Resulting from the conceptual encounter between a regular inner pattern, due to its polytechnic vocation, and local features linked with the geometry of the site, the building's shape fits in with the specificities of its immediate environment (Rappaz, 2014). Thanks to site topography, associated with the compactness of the building proposed and the creation of new landscaped areas, a central non-built space at the heart of the site has been laid out as a public meeting area. Landscaped with native plant species and featuring a storm-water retention pond, this public garden builds community ties with the surrounding district and acts as a representational space for an evolving urban area.

The notion of hybridization can also be seen in the structural and constructive development of the edifice. Three cores were built in situ in reinforced concrete in order to accommodate heavy laboratories, vertical distribution axes (staircases, lifts and elevators), sanitary facilities and the main technical ducts. By contrast, the rest of the structure is supported by a hybrid construction system combining wood and concrete which allows a reduction of grey energy, and offers a greater degree of flexibility for future adaptation (Veillon; Rey, 2012, 2015).

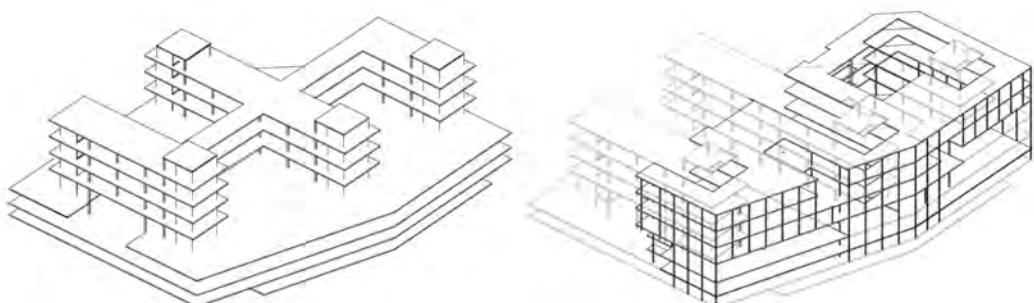


Figure 3. Structural principle including a hybrid construction system combining wood and concrete (Document: Bauart).

The fact that the composite wood-concrete elements were prefabricated in a workshop ensured greater accuracy, enabled faster production and reduced disturbances for the neighbourhood caused by construction work. In practical terms, approximately 4,000 m<sup>2</sup> of beams measuring 3.50 m by 5.00 m and 7.20 m were produced on the basis of a wooden assembly into which a 10 cm-thick layer of concrete was then poured. This combination meets high static requirements while reducing the quantity of grey energy used and providing the necessary soundproofing between floors.



Figure 4. Assembly of the hybrid elements on site (Picture: Yves André).

Based on the use of a wooden frame covered with fibre-wood-cement panels enclosing a layer of thermal insulation made of mineral wool, the façades were also produced in a workshop. Associated with wood-metal-framed glazing, this choice ensures regular continuity of the thermal shell, while rapidly achieving a weather- and air-tight building. Set up on the spot, an outer layer of rigid, recycled-glass plates on which glazed ceramic tiles have been fixed protects the inner layers of the shell and allows the building to benefit from the advantages of a ventilated façade.

### **Energy efficiency and environmental quality**

Microcity is so compact and its thermal envelope so efficient that its overall thermal performance is excellent. Taking into account a weighting between the building's different affectations, its basic heating needs ( $Q_h$ ) are 27.3 kWh/m<sup>2</sup> whereas the Minergie label requirement in this respect is equivalent to 30.2 kWh/m<sup>2</sup>. Thanks to dual-flow ventilation with heat recovery, controlled air renewal of the whole building greatly reduces loss of heat by ventilation during heating periods and covers a large part of heating needs by re-use of waste heat rejected by processes specifically linked with a research centre. This system allows air circulation from rooms producing more heat to other parts of the building, as well as transferring heat from one air flow (waste stale air expulsion) to another (incoming fresh air) without mixing them. For remaining heating needs during the cold season, the building has access to Neuchâtel's remote network of which approximately 30% is wood-generated (Rey, Frei & Baumann, 2013).

To minimise electricity requirements linked essentially with artificial lighting and laboratory equipment, several complementary measures were included right from the start in the design of the building including notably, for example, optimization of natural light thanks to long windows all along the external façades and two large skylights at the heart of the building, the integration of an artificial lighting system based on high-performance luminaires (with control over internal energy gains), use of natural ventilation in office areas and high-efficiency electrical devices.

But looking beyond its own quest for efficiency, Microcity is a driving force for the integration of renewable energies outside its own perimeter. It notably took part in the HOLISTIC approach (Holistic Optimisation Leading to Integration of Sustainable Technologies In Communities), a European research project whose primary objective was to reduce fossil energy consumption in the three cities of Neuchâtel (Switzerland), Dundalk (Ireland) and Mödling (Austria). In Neuchâtel, within five years, the approach has resulted in a reduction of over 23% of the fossil energy consumption in an area of approximately 1,5 km<sup>2</sup> between the railway station plateau and the lake (Consortium HOLISTIC 2013).

Covering Microcity's entire roof surface a large photovoltaic power plant – with 804 panels for a total of 1'271 m<sup>2</sup> – plays a key role in this dynamic approach.



Figure 4. Photovoltaic central on the roof connected to the city's power grid (Picture: Yves André).

The installation supplies 224'500 kWh annually to the Viteos electricity network, i.e. the equivalent of the consumption of some 64 households. 84 of the 804 panels on the roof are used as a testing platform devoted to research led by the EPFL's Photovoltaic and Thin-Film Electronics Laboratory (PV-LAB). In addition, the construction of Microcity played an important role in developing an underground canal loop using lake water for the ecological cooling of several buildings in the district. Thanks to this free-cooling, an annual electricity saving of 2.2 million kWh/yr, i.e. the equivalent of the electricity consumption of some 630 households, is expected by the electricity grid.

Table 1. Criteria of sustainability according to ranking in Recommendation SIA 112/1 (SIA, 2004).

<b>Environmental criteria</b>		
Building materials	Availability of raw materials	Analysis of life cycle, use of part of the excavation materials on the site
	Environmental impacts	Minimisation of environmental impacts (non-renewable primary energy NRE, CO emissions)
	Pollutants	Minimisation of pollutants in building materials
	Deconstruction	Use of separable, recyclable and recyclable materials
Operational energy	Heating or cooling requirements	Reduction of heating and cooling requirements
	Hot water energy requirements	Reduction of domestic hot water requirements (e.g. only cold water in sanitation areas)
	Electricity	Reduction of electricity requirements (natural light, natural ventilation, passive cooling, free cooling, high-performance appliances)
	Coverage of operational energy requirements	Use of renewable energy sources: photovoltaic solar roof, link-up with a loop using lake water for ecological cooling
Ground, landscape	Amount of land	Optimal density on the site (land-use coefficient of 2,0 = maximum for the City of Neuchâtel)
	Exterior spaces	« Green » garden with native species, providing habitat for local wildlife
Infrastructure	Mobility	Optimization of public transport use (bus-stop nearby)
	Operational waste	Selective sorting and optimization of building site waste materials, sorting plant for waste generated once operational
	Water	Ecological management of rain water (infiltration, retention pond in the garden)
<b>Socio-cultural criteria</b>		
Communal life	Integration, diversity	Diversity of users thanks to a mix of functions (offices, laboratories, auditorium, schools, restaurant)
	Social contact	Public garden for all users of the neighbourhood (researchers, employees, inhabitants, students, visitors)
	Involvement	Implication of users and neighbourhood associations in planning processes
Planning	Identity of the place, belonging	Recognition of the specific lay of the land, creation of a new urban landmark
	Customisable planning	Planning flexibility for the various laboratories
Operation, services	Proximity and functional diversity	Proximity of all services for users (e.g. shops, schools, nursery facilities, sports, leisure)
	Soft mobility	Link-up with transport network for pedestrians and bikes, 30 km/hr speed-reduced street zones around the site, self-service bike, car-sharing and electric car-sharing stations
	Accessibility and usability	Architectural details for wheelchair access and/or the visually impaired
Comfort, health	Security	Optimized security (controlled access, night lighting)
	Light	Optimization of natural light (e.g. long windows, skylights at the heart of the building)
	Indoor air quality	Choice of materials to reduce interior emissions (e.g. solvent-free paint, linoleum)
	Emissions	Reduction of magnetic fields
	Summer sun protection	Movable exterior sun protection
Economic criteria	Noise, vibrations	Optimized soundproofing, absorbers on all ventilation machines
	Site	Optimal use of the site (simultaneous creation of an institutional building and public spaces)
	Building structure	Creation of a new centre for a strategic urban site
	Structure and installations	Functional flexibility of buildings, possibility of extension in the masterplan
	Costs and life cycle	Synergy and partnership between the contracting authority (Canton of Neuchâtel), the operator (EPFL) and the users
Investment costs	Funding	Cost management integrating subsequent costs (renovation fund)
	External costs	Reduction of external costs through reduction of environmental impacts (mobility, energy, waste recycling)
	Operation and maintenance	Reduction of running costs through reduction of energy consumption
Running and maintenance costs	Renovation	Clear distinction between load-bearing parts (e.g. cores, pillars), and non-load-bearing and movable elements

Technically, a pumping plant was built near the lake in the water treatment plant compound; it was linked up with an under-lake pipe, which extracts water at a depth of 55 metres. At this depth, water remains at a practically constant 6° all year round and can thus supply a 1 km-long cool-water distribution network linking the many buildings concerned (Frésard, 2013).

In addition to energetic issues, the project is more broadly involved in simultaneous, optimized consideration of environmental, socio-cultural and economic criteria, which are synthesized according to ranking in "Recommendation SIA 112/1" (SIA, 2004).

Environmentally, the approach is based on solutions championing rational use of resources and minimisation of environmental impacts. Special care has been taken in the choice of materials presenting positive eco-balances. Close attention was also paid to the ecological management of building site waste materials (selective sorting at source and waste-to-energy process) and to subsequent deconstruction possibilities of the building components (severability of various parts and reversibility of assemblages). Great emphasis was placed on the ecological management of rainwater and the preservation of biodiversity, both in landscaping of outside areas (retention pond, native species) and regarding the roof (installation of nesting-boxes for bats in a technical element). Awarded the Minergie-ECO label, the proactive monitoring of these different challenges from the outset of the competition enabled the project managers to meet stricter requirements in the field of sustainable construction, while respecting the particularly short deadlines for completion (Rey, Frei & Baumann, 2013).

## Conclusion

From its conception right up to its implementation, the creation of this new branch of the EPFL in Neuchâtel was lucky enough to benefit from numerous territorial, political and institutional synergies. But, beyond these contextual opportunities, the approach has demonstrated that such synergies can enhance the pursuit of overall quality and more effective integration of sustainability criteria in project management.

This type of procedure is inherent in the very notion of a sustainable architectural project : it is what radically distinguishes it from the simple addition of resources, the mere juxtaposition of disconnected expertise and skills or the coordination of ad hoc solutions for a series of problems considered independently (Aiulfi, Rey, 2010). This route implicitly recognizes the importance of creativity in the complex processes of urban densification and the creation of sustainable buildings (Rey, 2013).

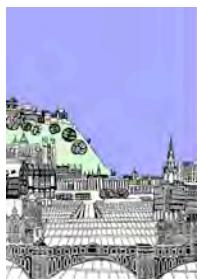
This vast area of research implies integrating an increasing number of skills in the development of the project, ideally from the programme's initial design sketches right up until the building becomes operational. In this regard, strategies tested within the framework of the Microcity project highlight the specific relevance of proactively integrating urban, landscape, architectural and construction issues from the start with the choice of an architectural project. The project process is thus fuelled by technological and operational considerations linked to other disciplines than architecture, without abandoning the spatial and expressive coherence, which is indeed its essence (Rey, 2014). In this spirit, far from being a burden, sustainability challenges can actually provide a "raw material" for architectural creativity and trigger dynamic commitment on the part of the various actors involved in finally putting the approach into practice (Rey, 2015).

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## References

- Aiulfi, D. & Rey, E. (2010). Les technologies vertes, matières premières pour la créativité des architectes. In : *Conférence MICRO 10*, Aula des Jeunes-Rives, Neuchâtel, September 2, 2010. Chevalley, M. (2014). Microcity à Neuchâtel. Palais de la microtechnique. *Bâtir*, 6, (pp. 29-35). Consortium HOLISTIC (2013). HOLISTIC : Retour d'expérience. Neuchâtel : *HOLISTIC, Rapport de synthèse*.
- Frésard, J. (2013). HOLISTIC, un laboratoire urbain de développement des énergies renouvelables. In : *Conférence des partenaires du projet HOLISTIC*, Neuchâtel, November 21, 2013.
- Rappaz, P. (2014). Microcity, le jeu de l'imbrication. *TRACES*, Dossier 05, (pp. 28-45).
- Rey, E. (2012). Swisswoodhouse, an innovative concept for sustainable modular housing. *PLEA 2012*, Lima, Peru, November 7-9, 2012.
- Rey, E. (2013). Vers une architecture durable. In E. Rey (Ed.), *Green Density*. (pp. 181-184). Lausanne : Presses polytechniques et universitaires romandes.
- Rey, E. (2014). Du territoire au détail. Lucerne : *Quart Verlag*, Collection Notatio.
- Rey, E. (2015). Sustainable architecture : towards integrated strategies from urban design to building component. In A. Khan, Allacker Karen (Ed.), *Architecture and sustainability : Critical perspectives*. Brussels : Sint Lucas Architecture Press.
- Rey, E. & Graf, S. (2015). Swisswoodhouse, innovative experimentation in sustainable modular housing : from interdisciplinary research to post-occupancy monitoring. *PLEA 2015*, Bologna, Italy, September 9-11, 2015.
- Rey, E., Frei, W. et Baumann, C. (2013). Hybridations durables. *TRACES*, Dossier 05, 46-57. SIA (2004). Construction durable - Bâtiment. *Recommandation SIA 112/1*. Zurich : SIA.
- Van der Poel, C. (2014). Processus convergents et identité urbaine cohérente. *TRACES*, Dossier 05, 18-27.
- Veillon, E. (2012). Microcity: un projethybride en bois-béton. *Batimag*, 1, 6-10.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Decision making factors of façade glass material selection in Tropical region, focusing on architectural designer

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**Abstract:** This study examines the decision-making systems for the selection of green building material for a glass façade through case studies in Singapore and Vietnam. The factors that influenced the choice positively were the building code, such as the national and international standards, or the stakeholder's original standards, particularly in Singapore. Conversely, the cost and the insufficient dynamics from the designer for the determination of material selection are the factors that negatively influence glass material selection in Vietnam. A comparison between both nations reveals that the decision makers are considerably diverse in Singapore and Vietnam. For the generalisation of the conclusions drawn in the tropical regions, detailed research focusing on the relationship between the stakeholders is required in future.

**Keywords:** decision making, glass façade, technical stakeholder, Singapore, Vietnam

### Introduction

Currently, the remarkable economic growth in the tropical region has induced an increase in the energy consumption of buildings. Energy saving in middle-income countries is extremely urgent in order to mitigate climate change. In that context, specific environmental building standards and rating systems have been promoted globally. The dissemination of green building techniques is a pertinent issue for building industries. The ASEAN countries located inside the Asian tropical region have introduced the Envelope Thermal Transfer Value (ETTV) for the estimation of the thermal performance of a building envelope. This was first introduced in Singapore, followed by several South East Asian countries, and referred to in the individual building code or in the local rating system as a building energy saving standard. It seems to assist in the development of an organised system of the green building regulation rather than in low-income countries.

To prospect the building techniques itself, the indigenous techniques controlling the heat acquisition in tropical region is the passive design with sunshade devices, natural ventilation and green vegetation, which are the energy saved building methodology by comparatively reasonable cost (Ogino *et al.*, 2015). However, in an urbanised city with rapid economic growth and an increasing demand for space owing to high population density, the vertical expansion of building scale seems logical in order to utilize the natural ventilation. As a result, the usage of specific glass materials that minimise heat absorption is expected to rise in the Asian tropical region.

Nevertheless, the success of sustainable utilisation of new technology may be limited because of the diversity in social systems and cultural characteristics. Even after the transfer of technology to a society, its successful adoption in the new society remains a matter of concern. In particular, research on the decision-making system for technology selection in the practical building construction process is considerably less. Ximena *et al.* (2014) researched the selection of methods in construction projects. However, there has not been sufficient research on glass, as a part of the building envelope with respect to building heating performance and energy consumption.

Thus, this study examines the decision-making system in the construction project process, focusing particularly on the façade glass material for large-scale buildings. As a regional characteristic, this paper defines the technical stakeholder as the building architect and engineer, who participate in the ordering, designing, and construction phases. This analysis contains both, positive and negative factors, and tries to reveal the decision making process that takes place among the architect, the client, and the contractor regarding material selection. As mentioned above, this research focuses on the building façade technology in environment, and the glass material, as a part of the building envelope, is the object of this case study. The purpose of this study is to reveal the adoption of technology, particularly building environmental techniques, on the process of construction and the surrounding social systems such as building standards.

### **Research Methodology**

Two rapidly urbanised cities with an increasing presence of multinational companies in the tropical region, Hanoi in Vietnam, and Singapore, were selected as case studies. Singapore is an economically advanced region in South East Asia, where numerous large-scale buildings are constructed using international technology, which is in turn transferred to the surrounding ASEAN region through such multinational construction projects. In contrast, Vietnam, located in the same tropical area, experiencing rapid economic growth and high-rise building construction, has not produced much research in building construction projects.

The data for this work was collected by the interview survey method, wherein technical stakeholders (Tab. 1 and Tab. 2) were interviewed. They included architectural designers and engineers who belonged to the architectural design office, the technical consulting firm, and the construction firm, and possessed practical experience of large-scale building construction projects. The supplemental survey included further interviews of the glass material suppliers and manufacturers. The content of the interview was designed to study the decision maker and the decision making factors in the selection of building material through the processes of ordering, designing, and construction. This survey comprehensively covers the technical aspects such as the requirement of glass material performance for building façade, the type of glass, performance of glass adopted in construction. In addition, the soft aspects of the decision-making process and the decision-maker are analysed from the interview results. For a national perspective, the building standard and code for the adoption of building materials are also included in this investigation. As case studies, this research selects newly constructed large-scale buildings such as offices, commercial and residential buildings. Seven case-interviews in Vietnam and nine case-interviews in Singapore were undertaken for this study.

Table 1. Case overview in Singapore

Case	A	B	C	D	E	F	G*4	H	I
Established year	1999	1883		1976	1976	2015	1974	1988	2013
Business	Design	✓		✓	✓	✓	✓	✓	✓
	Decide specification					✓		✓	✓
	Procurement			✓	✓	✓	✓		✓
	Construction			✓	✓	✓	✓	✓	✓
	Else		✓	✓	✓	✓			
Case building	Usage*1	R	C	O	M	O	M	O	M
	Structure	RC	S	RC+S	RC	RC	RC,S	RC+S	RC
	Floor	10		40	34,45	-	5,11	40	50
	Location*2	SIN	SIN	SIN	SIN	KL	SIN	SIN	SIN
	Project type*3	N	N	N	N	N	N	N	N

\*1 R: Residential, C: Commercial, O: Office, M: Mixed

\*2 SIN: Singapore, KL: Kuala Lumpur, \*3 N: New construction, REN: Renovation

\*4 Targeted building in case G is same building to targeted in case C

Table 2. Case Overview in Vietnam

Case	1	2	3	4	5	6	7
Established year	2010	2004	1991	1954	N/A	1996	1986
Business	Design	✓	✓	✓	✓	✓	✓
	Decide specification						
	Procurement						
	Construction			✓	✓		
	Else						
Case building	Usage*5	O	R	O	C	O	O
	Structure	RC	RC	RC+S	RC	RC	RC
	Floor	9	10	27	28	34	21
	Location*6	Hai	HN	HN	HN	HN	HN
	Project type*7	N	N	N, REN	N	N	N

\*5 R: Residential, C: Commercial, O: Office, M: Mixed

\*6 Hai: Hai phone, HN: Hanoi, \*7 N: New construction, REN: Renovation

### Building standards and code pertaining to the selection of glass

In Singapore, the building energy consumption constitutes 15.7 % of the total domestic energy consumption. One of the reasons behind this is the widespread use of air conditioners in high-rise buildings. The Building and Construction Authority (BCA) formulated the 'Green Mark' in 2005, a building assessment and certification system for environmental performance and sustainability. The award of Green Mark is regulated based on the building regulations, revised in 2008, for public buildings (Kitamura *et al.*, 2015).

The score is calculated using ratings in five categories, namely, energy efficiency, water efficiency, environmental protection, indoor environmental quality, and other green

features. The total score decides the type of the award from amongst the ‘platinum’, ‘gold plus’, ‘gold’, and ‘certified’ categories. In the case of non-residential buildings, for instance, the material used in the building envelope in air-conditioned (AC) areas counts for 12 points in the ETTV, and 35 points in the Non-AC areas in terms of envelope design and thermal parameter. It can be said that the selection of the glass is an important parameter in Singapore, as the relevant points constitute more than 30 % of the total score.

The Green Mark gold plus category requires an ETTV value that is less than or equal to  $42 \text{ W/m}^2$ , while the Green Mark platinum category has a limit of  $40 \text{ W/m}^2$ . In addition, the Non-AC area requires minimum direct west facing façade in the building design orientation, minimum west facing window openings, effective sun shading provision for windows on the west façade with a minimum shading of 30%, and better thermal transmittance (U-value) of the external west facing wall (less than or equal to  $2 \text{ W/m}^2\text{K}$ ) and roof.

Another assessment system of building performance and buildability in Singapore was listed by Yoshikawa *et al.* (2015), called CONQUAS: Construction Quality Assessment System for buildability, and constructability. The BCA recommends consultants to achieve the buildability score, and the builders to achieve the constructability score. There exist several standards for window constructability or façade grid design schemes. However, the Green Mark is the highest prior rating system and standard related with glass material.

In contrast, the Vietnam government presently promotes energy saving policies. The Ministry of Construction in Vietnam established the Energy Efficiency Building Code (EEBC) in 2005 to regulate the technical standard for buildings. It was revised in 2013 as QCVN 09:2013/BXD, particularly the sections regarding the building material and construction method for design. However, the detailed specifications are beyond the scope of the paper (Ogino *et al.*, 2015). The thermal performance of the building envelope, the U-value (Overheat transfer value, 0.56–1.80) and the overall thermal transfer value (OTTV) less than or equal to  $60 \text{ W/m}^2$  are recommended. The solar heat gain coefficient (SHGC) for each orientation and the visual light transmission (VLT) are also mentioned.

As stated by Ogino, *et al.* (2015), large-scale projects adopt the Euro code in Europe or the ASHRAE standard in the United States. The Vietnam Green Building Council (VGBC) aims to promote the construction of green buildings, and was established in 2007 as a non-profit organisation. It developed the green building rating tool, ‘LOTUS’.

Table 3. Standards referred to in Singapore

	National standards	International standards	Green Building Certification	Original guideline
Case A	Green Mark, SS	ASTM, BS	-	-
Case B		ASTM,	-	-
Case C		ASTM, AS, BS	-	-
Case D		ASTM, BS	-	Glass manufacturer
Case E		AS, EN, BS, ASTM, ISO	LEED, GBI	-
Case F		BS, ASTM, AS	-	Façade consultant
Case G		BC <sup>*8</sup> , CP <sup>*9</sup>	-	Façade consultant
Case H		BS, AS/NZA, AAMA	LEED	-
Case I		N/A	-	Domestic

\*8 BC: British Columbia Building Code, \*9 CP: Code of Practice

Tab. 3 displays the referred standards for construction projects in Singapore. In addition to the national building codes 'Green Mark' and Singapore standard (SS), international standards such as ASTM international, Euro code (EN), British Standard (BS), Australian Standard (AS), and ISO are referred during construction projects besides the original guidelines of the consultant. The reason can be pointed out that BCA nominated some of code to refer.

However, in the case of Vietnam, as depicted in Tab. 4, only the national building codes such as the QCVN and the TCVN are achieved in almost all the cases. Thus, it is clear that Singapore follows global standards, but Vietnam seeks to follow only its national code and green building certification. The difference stems not only because of suggestions from the authorities, but also from the diversity of the participants in projects in Singapore. Particularly, the façade consultant and multinational enterprises promote this switch to higher global standards.

Table 4. Standards referred in Vietnam

	National standards	International standards	Green Building Certification
Case 1	-	-	-
Case 2	QCVN, TCVN	-	LOTUS
Case 3	QCVN, TCVN	-	-
Case 4	QCVN, TCVN	-	-
Case 5	QCVN, TCVN	-	-
Case 6	QCVN, TCVN	-	-
Case 7	QCVN, TCVN	-	-

### Material selection in the construction process

In Vietnam, the requirements in the order from a client specify the building scale, usage, and form. However, the material usage in this process is not specified. In Singapore, the Design Build is a common contract, where the client seeks the requirement performance concretely.

The core technical stakeholders in the design process are the architectural designer, and the façade consultant in Singapore (Tab. 5). Several options for glass materials for the façade are suggested, and in several cases, the supplier and the green consultant also participate in the decision-making process. In particular, the technical specification documented minutely, reflecting the original standard proposed for usage by the façade consultant is the principal factor behind glass material selection in Singapore. However, the cognition of the stakeholders in the same case, such as in cases C and G, is slightly different from the decision maker.

The suggested material is a low iron, clear, floating glass in the form of double glass, tempered glass, or low-E coating. For specific cases, the triple layer silver coating glass is adopted. The prominent reasons for the adoption of the suggested high performance glass are summarised in the following three points. Firstly, such glass is adopted in order to follow the national building code. The BCA building regulation authority of Singapore mandates the green building labelling system 'Green Mark certification', which requires the material performance and design to pass a certain ETTV value. The second reason, in some cases, is to attain international building standards, because such buildings are labelled as LEED: Leadership in Energy and Environmental Design, by the U.S. Green Building Council. The last

factor is a specific requirement by the façade consultant. The international façade consultancy has its own standards, which are fixed, and mandatory for the projects they participate in. Moreover, the high performance materials are selected by stakeholders to differentiate themselves from their competitors.

Table 5. Glass material proposer and adoption for construction in Singapore

Case		A	B	C	D	E	F	G	H	I
Propose		✓	✓	✓	✓	✓	✓	✓	✓	✓
Proposer	Client		✓				✓			
	Designer		✓				✓			
	Façade consultant		✓	✓	✓	✓	✓	✓	✓	✓
	Green consultant						✓			
	Engineer									
	Supplier									
	Else			✓						
Decision maker	Client	✓	✓	✓	✓		✓			
	Designer	✓	✓	✓	✓	✓	✓			✓
	Façade consultant	✓		✓	✓	✓	✓	✓	✓	✓
	Green consultant						✓			
	Supplier									
	Else							✓		
	Contractor	✓		✓						
Adoption on construction			✓	✓	✓	✓	✓	✓	✓	✓

Table 6. Glass material proposer and adoption for construction in Vietnam

Case		1	2	3	4	5	6	7
Propose		✓	✓	✓	✓	✓	✓	✓
Proposer	Client		✓					✓
	Designer	✓	✓	✓	✓	✓	✓	✓
	Façade consultant							
	Engineer							
	Supplier							
	Else		✓					
Adoption on construction		(✓)	✓		✓		✓	

The adoptability of the suggested material in the design phase is investigated (Tab. 7). In all cases in Singapore except one, the material specified was adopted. To select the most appropriate material, a VMU (Visual mock up), a PMU (Performance mock up), material testing and performance calculation using simulation and software were conducted in the respective cases. This demonstrates the various activities conducted to determine the best material in terms of the performance, aesthetics, buildability, cost etc. in Singapore.

In Vietnam (Tab. 6), on the other hand, the primary technical stakeholder in the design phase is the architectural designer. The proposals for glass materials to be used are also presented by him. Simple requirements such as double glazing glass or low-E coating,

reflective glass or single glass are proposed. The reason is merely the achievement of the national building code, and includes factors affecting building performance such as solar heat reduction, reflectivity, safety, and also aesthetic factors such as colour property and designability.

Table 7. Decision making for the selection of glass material in Singapore

	Selection activity	Decision making factor
Case A	VMU, PMU, Material testing	Performance, Aesthetics
Case B	VMU, PMU, Soft data	Performance, Aesthetics
Case C	Calculation, Experience, Spec, Material testing, VMU	Performance, Aesthetics
Case D	VMU, Sample, Calculation	Performance, Procurement
Case E	Software, Soft data, VMU	Buildability, Cost
Case F	Simulation, VMU, Experience	Performance
Case G	Software, Experience, VMU, Wind tunnel test, Calculation	Performance
Case H	VMU	N/A
Case I	VMU, data, sample	Performance

Through the analysis of this study in Vietnam, it was found that the practical façade material selection at the construction stage was determined by the client and the contractor. Furthermore, locally procurable materials were adopted and the imported materials proposed by a designer were rejected. As the contractor and sub-contractor are generally nominated by the client, the determination of the building standards to be followed depends on the client's opinion. The major factors affecting decision-making in Vietnam are budget limitations and material cost. However, if trust is established between a client and a designer, the designer's proposal and advice are overwhelmingly adopted even in the construction phase.

## Conclusion

This paper studies the decision-making system for the selection of green building material for a glass façade. The factors responsible for a positive outcome in Singapore include the building code (national and international), and the high standards set by the stakeholders themselves. Conversely, cost and insufficient dynamics of the designer for determination of glass are responsible for a negative outcome in the case of glass material selection in Vietnam. The comparison of the decision making process between these nations reveals considerable diversity. In addition, this paper also points out that each stakeholder cognised differently in the analysis of the Singapore case study. Further detailed research focusing on the relationship between the stakeholders is necessary for generalisation of the conclusions of this study for other tropical countries.

## References

- Building Construction Authority, Singapore. (2005). Green Mark for New Non- Residential Buildings Version NRB/4.1
- Centre for window and cladding technology. (1992). A comparative study of the façade industry in the UK, Europe, Japan and the USA,
- Kitamura, S., et al, (2015). Research on energy saving house in hot and humid areas in Asia: 1 Research

- in Taiwan, Tokyo, Japan, 1031-1032 September 2015. Architectural Institute of Japan: Annual conference
- Ministry of Construction, Vietnam. (2013). QCVN 09:2013/BXD, National Technical Code for Building Energy Efficiency
- Ministry of Science and Technology, Vietnam. (2010). TCVN 5687:2010, Ventilation-air conditioning - Design Standards
- Ogino, S., et al, (2015). Research on energy saving house in hot and humid areas in Asia: 2 Research in Vietnam, Tokyo, Japan, 1033-1034 September 2015. Architectural Institute of Japan: Annual conference
- Ximena, F., Alfredo, S. (2014). Selection of construction methods for construction projects: A knowledge problem. Journal of Construction and Engineering and Management, 140(4), B4014002, pp.(1-7)
- Yoshikawa, et al, (2015). Foreign Workers Accepting System in Singaporean Construction Site, Tokyo, Japan, 139-140 September 2015. Architectural Institute of Japan: Annual conference



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## Sustainable Urban Planning and Green Building Assessment Tools for Bangladesh, a Country of Tropical Region

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**Abstract:** Built environment has profound impact on our natural environment, our economy, as well as personal health & productivity. Building construction and operation have extensive direct and indirect impacts on the environment. Green building design has environmental, economic and social elements that benefit all building stakeholders including owners, occupants and the general public. But, at present, the sustainability measures are barely on the agenda of the Building Regulation formulation process in Bangladesh. Therefore it is an essential need for Bangladesh to build such a rating system to access the environmental acceptability of buildings. It is important to note that from country to country the considerations for those rating systems will change as the environmental conditions; level of development and the availability of resources vary from place to place. The main purpose is to develop such a rating system to provide a remarkable service in assessing the buildings in terms of environmental acceptability while providing leadership to develop green solutions. This study focuses on Sustainable Site Planning & Management (SM) which includes: Site Planning (Site Selection, Brownfield Redevelopment, Development Density & Community Connectivity, Environment Management), Construction Management (Earthworks - Construction Activity Pollution Control, Quality Assessment System for Building Construction Work, Workers' Site Amenities), Transportation (Public Transportation Access, Green Vehicle Priority - Low Emitting & Fuel Efficient Vehicles, Parking Capacity) and Design(Storm water Design, Greenery & Roof, Building User Manual). Thorough analysis has been conducted on the intends and impacts of the all categories of 'Sustainable Site' of the selected three rating systems of tropical countries. The analysis will find out the assessment criteria and points of 'Sustainable Site' for Bangladesh and then establish guidelines for the sustainable built environment of Bangladesh and will also recognize and reward in environmental leadership.

**Keywords:** Sustainable Development, Built Environment, Building rating System, Environmental leadership

### Introduction

The world is facing an immense challenge, to create sustainable buildings for the future. Buildings are the major source of demand for energy and construction materials produce significant amount of by-product greenhouse gases. Studies show that the building sector accounts for over 40 percent of world's energy requirements and a large percentage of the present energy consumption and carbon dioxide generation could be saved by applying certification standards to new and refurbished buildings. Most of the leading countries have

their own green building councils to govern their green rating for building structures. For the time being, there is no real consensus on what is a green building and the architectural design community and the scientific and building research community are a long way apart. Therefore, it is an essential and timely need for Bangladesh to build such a rating system to assess the environmental acceptability of buildings. It is important to note that from country to country the considerations for those rating systems will change as the environmental conditions; level of development and the availability of resources vary from place to place.

The main purpose is to develop such a rating system of Bangladesh for one selected sustainability issue to provide a remarkable service in assessing the buildings in terms of environmental acceptability while providing leadership to develop green solutions in the future for new developments and incorporate such concepts to existing buildings by retrofitting them to make them sustainable. The importance of various domains and aspects of Rating Systems were identified by a survey named "Sustainability Rating Systems for Buildings: Comparisons and Correlations (Chandratilake, S.R. and Dias,W.P. S, 2013) and it was found that " Sustainable Sites" is the most important domain. Energy and atmosphere, materials and resources, water efficiency and indoor environmental quality are respectively in the top order. Therefore, this study intends to guide how to develop and generate sustainable site for built environment to reduce its environmental impact and ensure that new buildings remain relevant in the future and existing buildings are refurbished and upgraded properly to remain relevant. The analysis will find out the assessment criteria for Bangladesh and then establish guidelines for the sustainable built environment of Bangladesh and will also recognize and reward environmental leadership.

### **Objective of the Study**

A green building is designed to use less energy and water, improved indoor air quality and to reduce the life-cycle environmental impacts of the materials used. A green rating system mainly aims in fundamentally in changing the built environment by creating energy-efficient, healthy, productive buildings that reduce or minimize the significant impacts of buildings on the environment. Although the rating system should be based on world's best practice for Green Buildings, local conditions has to be very efficiently incorporated. A local certification system will be definitely less expensive and will attract more local developers.

The concept of "Green Buildings" aims at increasing the efficiency with which buildings use resources such as energy, water and materials while reducing the impact of buildings on human health and its surrounding environment during its lifecycle, through better design, construction, operation, maintenance and removal and recycling of waste. This rating system for Bangladesh will provide a rigorous road map to building green and there is no doubt that it will receive support from both public and private sectors and become the rating tool of choice. The study presented in this paper is focused on providing strategies of Green Building Rating System for Bangladesh.

This study is limited to analysis on Sustainable Site Planning & Management to limit the scope of work. A general analysis on all the other Areas of Assessment can also be done to compare with the international standards and generate recommendations and design guidelines that can be applied easily in context of Bangladesh.

## **Methodology**

Some literature reviews are done to gather general background knowledge about city morphology of Dhaka and the climatic context of Dhaka city. Then various latest documents on Environmental Rating System are compared to understand how to generate guidelines. After thorough analysis of the intends and impacts of the all categories of ‘Sustainable Site’ of the selected three rating systems of tropical countries, categories and respected points are recommended for Bangladesh.

## **Energy condition in Dhaka**

Bangladesh is lying between  $20^{\circ}34' N$  to  $26^{\circ}33' N$  and  $88^{\circ}01' E$  to  $92^{\circ}41'E$ . Dhaka, the capital of Bangladesh, is one of the mostly populated cities in the world and at present is inhabited by apx. 16 million people. The city is being expanded rapidly with numerous new constructions. The built environments of Dhaka city are often uncomfortable in comparison to its rural surroundings. Current demand of new housing units each year is 50,000 with a backlog of 300,000 units. It is believed that the energy performances of Dhaka city buildings are highly unsustainable due to its site selection, construction practice; narrow setbacks which do not allow enough daylight to penetrate. The site selection, building design and construction of a new building play an active role in causing significant changes in the urban micro-climate by its geometric profile, material etc. So, at the stage of policy making and site planning, the issues of ensuring comfort in urban spaces relying on natural system should be an important element in the urban design agenda.

## **Literature Review**

There are different types of rating system in different countries. To provide guidelines for Bangladesh, the rating systems of tropical countries have been studies. Those are:

- The Green Building Index (GBI) of Malaysia
- LEED Rating System in India
- GBCSL of Srilanka

### ***The Green Building Index (GBI) of Malaysia***

The Green Building Index is an environmental rating system for buildings developed by PAM (Pertubuhan Arkitek Malaysia / Malaysian Institute of Architects) and ACEM (the Association of Consulting Engineers Malaysia). The Green Building Index is Malaysia's first comprehensive rating system for evaluating the environmental design and performance of Malaysian buildings based on the six (6) main criteria of Energy Efficiency, Indoor Environment Quality, Sustainable Site Planning & Management, Materials & Resources, Water Efficiency, and Innovation. The Green Building Index is developed specifically for the Malaysian tropical weather, environmental and developmental context, cultural and social needs.

### ***LEED Rating System in India***

Following the formation of the Indian Green Building Council (IGBC) in 2001, the membership quickly realized that one of the priorities for the sustainable building industry was to have a system to define and measure “green buildings”. To this end the IGBC has set up the LEED India Core Committee with the objective of indigenizing the LEED rating system

for the Indian context. The composition of the committee included architects, engineers, building owners, developers, manufacturers and other industry representatives. This cross section of people and professions added richness and depth, both to the process and to the ultimate product. The first LEED India rating programme, referred to as LEED India Version 1.0, was launched during the Green Building Congress Conference in October 2006. Several versions of the rating system, as suited for various project types, have been developed since then. The LEED 2011 for India Green Building Rating System is a voluntary, consensus-based, market driven rating system based on existing, proven technology & processes. It evaluates environmental performance from a whole building perspective over a building's life cycle, providing a definitive standard for what constitutes a "green building".

### ***Green Building Council of Sri Lanka (GBCSL)***

The concept of "Green Buildings" aims at increasing the efficiency with which buildings use resources such as energy, water and materials, while reducing the impact of buildings on human health and its surrounding environment during its lifecycle, through better design, construction, operation, maintenance and removal and recycling of waste. The Green Building Council of Sri Lanka (GBCSL) came into existence as a result of an emerging trend towards applying the greener concepts for built environment. The Mission is to develop the sustainability of the built environment by transforming the way it is planned, designed, constructed, maintained and operated and drive the adoption of green building practices through market-based solutions, while helping to forge a new partnership between government, industry and other stakeholders.

### **Area of Assessment and Classification**

Each Rating system has some assessment area and a different level of certification. Three Rating systems of three different tropical countries are compared below:

#### ***Green Building Index of Malaysia***

##### **Overall points score**

1. Energy Efficiency	35
2. Indoor Environmental Quality	21
<b>3. Sustainable Site Planning &amp; Management</b>	<b>16</b>
4. Material & Resources	11
5. Water Efficiency	10
6. Innovation	7

Table 01: Green building index (GBI) classification

Rating	Points GBI
Platinum	86+ points
Gold	76 to 85 points
Silver	66 to 75 points
Certified	50 TO 65 points

#### ***LEED Rating System in India***

##### **Overall points score**

1. Sustainable Sites (SS)	<b>28</b>
2. Water Efficiency (WE)	10
3. Energy and Atmosphere (EA)	37
4. Materials and Resources (MR)	14
5. Indoor Environmental Quality (IEQ)	15

6. Innovation in Design (ID)	6
7. Regional Priority (RP)	4

Table 02: Credit Point Thresholds *LEED Rating System in India*

Rating	Point
Platinum	80 points and above
Gold	60 - 79 points
Silver	50 - 59 points
Certified	40- 49 points

### **GBCSL of Srilanka**

#### **Overall points score**

1	Management	4
2	Sustainable Sites	25
3	Water Efficiency	14
4	Energy & Atmosphere	21
5	Materials & Resources	21
6	Indoor Environmental Quality	13
7	Innovation & Design Process	4
8	Social & Cultural Awareness	3

Table 03: Credit Point Thresholds *GBCSL of Srilanka*

Rating	Point
Platinum	70 points and above
Gold	60–69points
Silver	50–59 points
Certified	40–49 points

### **Recommendations for Bangladesh for ‘Sustainable Site’:**

After thorough analysis of the intends and impacts of the all categories of ‘Sustainable Site’ of the selected three rating systems, the following categories and respected points are recommended for Bangladesh:

#### ***Site Selection (1 Point)***

During the site selection process, preference should be given to sites that do not include sensitive elements or restrictive land types. Select a suitable building location should be selected and the building should be designed with a minimal footprint to minimize disruption of the environmentally sensitive areas identified above. Strategies should be included for stacking the building programme, tuck-under parking and sharing facilities with neighbours.

#### ***Brownfield Redevelopment (1 Point)***

During the site selection process, preference should be given to brownfield sites where development is complicated by environmental contamination, thereby reducing pressure on undeveloped land. This would typically involve old rubbish tips, former mining land, old factory sites, etc. Tax incentives and property cost savings should be identified. Site development plans should be coordinated with remediation activity, as appropriate.

## ***Development Density & Community Connectivity (2 Points)***

During the site selection process, preference should be given to urban sites with pedestrian access to a variety of services.

### **i. Development Density**

A new building will be constructed or an existing building will be renovated on a previously developed site and in a community with a decided minimum density.

### **ii. Community Connectivity**

A new building will be constructed or an existing building will be renovated on a site that meets the following criteria:

- is located on a previously developed site
- is within 1/2 mile (800 meters) of a residential area or neighbourhood
- decided units per acre
- is within 1/2 mile (800 meters) of at least 10 basic services
- has pedestrian access between the building and the services

Basic Services include, but are not limited to:

1) Bank; 2) Place of Worship; 3) Convenience / Grocery; 4) Day Care; 5) Police Station; 6) Fire Station; 7)Beauty; 8) Hardware; 9) Laundry; 10) Library; 11) Medical / Dental; 12) Senior Care Facility; 13) Park; 14)Pharmacy; 15) Post Office; 16) Restaurant; 17) School; 18) Supermarket; 19) Theatre; 20) Community Centre; 21) Fitness Centre.

## ***Environment Management (2 Points)***

### **i. Greenfield Conservation**

Greenfield sites are those that are not previously developed or graded and remain in a natural state. Rural landscapes are considered the same as greenfield sites. A rural landscape is a natural area modified by agro-forestry-pastoral activities, with environmental, aesthetic, cultural and historical values, resulting from the interrelationship between its physical and biological aspects and traditional human activities. These Greenfield sites have to be conserved for the well being of the world.

### **ii. Maximize Open Space**

A site survey has to be performed to identify site elements and adopt a master plan for developing the project site. Select a suitable building location and design the building footprint to minimize site disruption. Strategies should include stacking the building program, tuck-under parking and sharing parking facilities with neighbours to maximise the amount of open space on the site.

## ***Construction Management (2 Points)***

### **i. Earthworks - Construction Activity Pollution Control (1 Point)**

An erosion and sedimentation control plan should be created during the design phase of the project. Considerations should be done to employ strategies such as temporary and permanent seeding, mulching, earthen dikes, silt fencing, sediment traps and sediment basins.

### **ii. Workers' Site Amenities (1Point)**

Proper safety and security plan should be adopted for workers of the projects. Pollution from construction activities should be reduced by controlling pollution from waste and rubbish for workers.

### **Transportation (3 Points)**

#### **i. Public Transportation Access (1 Point)**

Public transport facility should be ensured within walking/cycling distance from the selected site of development.

#### **ii. Green Vehicle Priority (1 Point)**

Buildings should be designed with transportation amenities, such as bicycle racks and shower/changing facilities. Other transportation amenities, such as, alternative-fuel transports, refuelling stations should be adopted. The costs and benefits of refuelling stations can be shared with neighbours.

#### **iii. Parking Capacity (1 Point)**

Parking lot/ garage size should be minimised. Sharing parking facilities with adjacent buildings Considered. Parking areas should be shaded to reduce the heat island effect. A transportation survey of future building occupants should be performed to identify transportation needs.

### **Stormwater Design – Quantity and Quality Control (2 Points)**

The project site should be designed to maintain natural stormwater flows, by promoting infiltration. Vegetated roofs, pervious paving and other measures should be specified to minimise impervious surfaces. Stormwater should be reused for non-potable uses, such as landscape irrigation, toilet and urinal flushing, and custodial uses.

### **Greenery and Roof (2 Points)**

Strategies should be employed to select proper materials and landscaping techniques that reduce the heat absorption of exterior materials.

### **Tenant Design and Construction Guidelines (1 Point)**

A copy of the tenant design and construction guidelines should be provided to tenants.

### **Regional Priority (4 Points)**

An incentive should be provided for the achievement of credits that address geographically-specific environmental priorities.

## **Conclusion**

With the development of economy and life quality, high energy consumption of large scale public buildings is becoming more and more noticeable in Dhaka city of Bangladesh. Most of the techniques and resources, that are being used today in Bangladesh, account for environmental degradation. Therefore, it is high time to search for new designs idea to reduce the impact to the environment. Buildings' energy efficiency has come to the forefront of political debates due to high energy prices and climate change concerns. This paper presents a holistic analysis on how to minimize the adverse effect on the site of development.

This Study indents to provide a rating System of "Sustainable Site and Management" for built environment of Bangladesh, which set performance standards for certifying all development works of all functional buildings (commercial, institutional buildings, high-rise residential) of all sizes, both public and private. The intent is to promote high performance, healthy, durable, affordable, and environmentally sound practices for new and existing buildings. The Government will give incentives to builders and the building products solutions which achieve the bench marks, set by the Rating system. This will be a major step

towards adopting a sustainable practice in development of buildings to utilize the natural resources and make efficient designs to utilize nature for the betterment of the mankind.

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## References

- Abul K Azad, S.W. Nashreen J. Sultana, "State of Energy consumption and Co2Emission in Bangladesh" AMBIO: A Journal of the Human Environment" Volume: 5, issue March 2006, article pp 86-88.
- Ahmed, K. S. (1995). Approaches to Bioclimatic Urban Design for the Tropics with Special Reference to Dhaka, Bangladesh. Unpublished Doctoral Dissertation, Environment and Energy studies program, AA School of Architecture, London 1996. 33-105.
- Alam, M.S., Kabir, E., Rahman, M.M. & Chowdhury, M.A.K. 2004. Power Sector Reform in Bangladesh: Electricity Distribution System. *Energy*, 29 (11): 1773-1783.
- American Society of Heating, Refrigerating Air-conditioning Engineers Inc. (ASHRAE), ANSI/ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy, American Society of Heating Refrigerating and Air-conditioning Engineers Inc., Atlanta, USA, 2004
- Anderson, Jane. The Green Guide to Specification An environmental profiling System for Building Materials and Components , Third Edition
- Bangladesh Centre for Advanced Studies, Climate Change Vulnerabilities for Urban Areas in Bangladesh: Dhaka as a Case, Bonn, Germany, 2010.
- BBS. 2008. Statistical Pocket Book of Bangladesh 2007.Bangladesh Bureau of Statistics Planning Division: Ministry of Planning.
- Chandratilake, S.R. and Dias,W.P. S. 2013. "Sustainability Rating Systems for Buildings: Comparisons and Correlations" Elsevier, Energy. Volume 59, 15 September 2013, Pages 22–28
- [9] Dhaka Mirror. 2009. Sufferings of City Dwellers Mount Due to Severe Power Crisis. [Online]. Available: <http://www.dhakamirror.com/?p=3428>. [Accessed 10 March, 2016].
- GBI ASSESSMENT CRITERIA for NON-RESIDENTIAL NEW CONSTRUCTION (NRNC) First Edition, April 2009,Version 1.0
- Hancock, J.M.2006. Dhaka Electric Supply Company Hosts Final USEA/USAID Utility Partnership Exchange Program With U.S. Distribution Utilities. Retrieved 15 December, 2008, from [http://www.usea.org/Programs/EPP/EPP\\_News/DESCO\\_12\\_2006.pdf](http://www.usea.org/Programs/EPP/EPP_News/DESCO_12_2006.pdf).
- LEED 2011 For India, Green Building Rating System , Abridged Reference Guide, September 2011.
- Mozumder,P. & Marathe, A. 2007.Viewpoint: Causality Relationship Between Electricity Use and GDP in Bangladesh. *Energy Policy*, 35 (1): 395-402.
- Oke, T.R., 1988: Street design and urban canopy layer climate. *Energy and Buildings* 11, 103-113.
- Rahman, A. & Mallick, D.L. n.d. Climate Change Impacts on Cities of Developing Countries: A Case Study on Dhaka. Bangladesh Centre for Advanced Studies. [Online]. Available: [http://www.c40tokyo.jp/en/pdf/keynoteLecture\\_symposium/dl\\_mallick.pdf](http://www.c40tokyo.jp/en/pdf/keynoteLecture_symposium/dl_mallick.pdf). [Accessed 20 December, 2015].
- Saleque, A.K.2008. Bangladesh Energy Security – Entering Red Zone. [Online]. Available: <http://energybangla.com/index.php?mod=article&cat=SomethingtoSay&article=105>[accessed 17 December, 14]
- Sezgen, O, Huang YJ. Lighting/HVAC Interactions and Their Effects on Annual and Peak HVAC Requirements in Commercial Buildings. Report no. LBL-36524. Berkeley, CA: Lawrence Berkeley National Laboratory, 1994.
- Tuhin, F.2008. Revisiting the Energy Scenario in Bangladesh.[Online]. Available: <http://energybangla.com/index.php?mod=article&cat=SomethingtoSay&article=1055>. [Accessed on 17 December, 2016].
- Upmanis, H., 1999: The influence of sky view factor and land use on city temperatures. In Upmanis, H.: Influence of Parks on Local Climate. Earth Sciences Centre, Göteborg University A 43, paper 3.
- Vangtook, P. & Chirattananon, S. 2007. Application of Radiant Cooling as a Passive Cooling Option in Hot Humid Climate. *Building and Environment*, 42 (2): 543-556.



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## Domestic thermal insulation in Wales, UK: future demand scenarios, embodied impact and regional capacity to match demand

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**Abstract:** Thermal insulation is fundamental to reducing energy demand and improving comfort in housing. The demand for insulation products might be expected to rise in the UK to achieve National and International energy targets. The majority of products currently installed in UK housing are manufactured from mineral and fossil resources, with research suggesting that locally-manufactured biomass-based products have lower embodied impact than these more conventional products. However, the overall benefits and drawbacks brought about by a large-scale shift to biomass-based products together with the availability of local resources are yet to be investigated. This paper looks at the supply of different insulation products with a long-term and large-scale perspective focusing on the case of Wales, UK. Combinations of conventional and biomass-based insulation products are modelled to produce future supply scenarios based on forecasted demand to 2050 appropriate for new and retrofitted dwellings. The embodied environmental impact of these future scenarios is estimated using life-cycle assessment. The requirements for renewable biomass-based products are compared to the regional capacity to supply such levels of resources. Product prices are surveyed to determine current market conditions in the UK.

**Keywords:** insulation, embodied impact, life cycle assessment, natural resources, regional supply.

### Introduction and research aim

Thermal insulation can improve the comfort and energy performance of dwellings by reducing heat transfer through the building envelope. The uptake of energy-efficiency measures is likely to rise in new and retrofitted dwellings, which will cause an increase in demand for insulation products. Currently, the majority of insulation products used in domestic retrofit and new build are manufactured using fossil and mineral resources (AMA Research, 2015). Despite the fact that the overall life-cycle balance of insulation products is generally positive, at least in terms of carbon emissions due to energy savings, the large use of fossil and mineral-based “conventional” products have been criticised due to the associated Embodied Environmental Impact (EEI). Life-Cycle Assessment (LCA) studies have indicated that biomass-based products can have lower EEI than conventional ones (Norton 2008; Asdrubali et al., 2015), especially in terms of global warming potential due to the sequestration of carbon in the product. Due to higher prices and small manufacturing scale the uptake of biomass-based products in the UK has been limited to date (Hayward et al., 2013). While an increase in manufacturing of biomass-based products might partially address the issue of higher price by reducing marginal cost, the extent to which the prices of these products needs to decrease to become competitive with conventional ones needs to be clearer. Very few studies compare the market price of insulation products on an equal

basis. A shift from conventional to biomass-based products could also be stimulated by evidence of the potential for EEI reduction together with confirmation of the availability of local resources to meet a significant demand increase of such products.

Wales has been selected as a case study to investigate supply of different insulation products with a long-term and large-scale perspective. The Welsh Government has embedded sustainability in its legal framework, and has successfully funded the large scale rollout of energy-efficiency measures (including envelope insulation) such as the Arbed programmes (Patterson, 2016). Fuel poverty is a significant issue in Wales, thus thermal insulation measures to reduce the energy demand and improve the occupants' comfort will help to reduce household expenditure on energy bills. Finally, the Welsh territory and economy might have the potential to supply natural resources and manufacture three types of biomass-based insulation products: sheep wool, hemp fibre and wood fibre.

*Sheep wool* insulation is made from low-quality wool, which is currently produced in Wales as by-product of the sheep meat sector. Two of the main manufacturers of sheep wool insulation in the UK are partially supplied by producers in Wales. Hemp and wood fibre products are not currently produced in Wales but the potential exists. *Hemp fibre* insulation is made from industrial hemp, which could be cultivated in Wales (Allen, 2016), and *wood fibre* insulation is made from softwood chips, which are produced in Wales as a secondary product of the timber industry. These three biomass-based insulation products have been identified to have the most opportunity in terms of local resource availability in the context of Wales.

This paper will present the potential for reducing the EEI of domestic insulation in Wales through the use of local biomass-based products while considering possible constraints associated with the availability of local resources and product prices. The paper will: 1) estimate the *change of the EEI* of insulation supply caused by a progressive substitution of conventional products with biomass-based ones; 2) compare the resulting *demand for biomass insulation* products to indicators of the capacity of the Welsh territory and economy to supply such resources; 3) determine and compare the current range of *insulation products prices* based on thermal resistance. The work presented in this paper is part of a larger piece of research, as part of a PhD degree.

## Methodology

Research is carried out in four steps: 1) on the basis of a forecast of the future demand for insulation in Wales (Varriale, 2016), one baseline and three alternative supply scenarios are built to model different product combinations; 2) the resulting quantities of products are used to estimate the EEI of the supply scenarios through LCA; 3) the resulting demand for biomass is compared to indicators of regional capacity; 4) prices and technical data of insulation products sold in the UK are collected and analysed.

The forecast of the demand for insulation in Wales to 2050 is generated (Varriale, 2016) by combining geometric data on the Welsh domestic stock (Welsh Government, 2013; ONS, 2014), a projection of construction activity based on historical records (Welsh Government, 2014a), and the current legal requirements for thermal insulation in dwellings (Welsh Government, 2014b). External and Internal Wall Insulation (EWI and IWI) and loft insulation are included in the analysis for retrofitted dwellings, and external wall, roof and ground floor insulation in newly built dwellings. The graph on the left of Figure 1 presents the forecasted insulation product demand, quantified in square meters of insulation with thermal resistance of 1 K/W. Overall demand is predicted to rise until 2026 and then start to

decline. This forecast is based on a combination of demand profiles for insulation: in retrofitted dwellings, a peak will be reached in the first half of the time period; for new dwellings, growth is determined by a construction rate of 0.65% (Varriale, 2016).

The graph on the right of Figure 1 presents the baseline supply scenario, which models a business-as-usual condition where all the demand for insulation is met with conventional products, which currently occupy about 90% of the UK market (OFT, 2012a). Five conventional fossil and mineral-based products are included: stone wool, glass wool, Polyurethane/polyisocyanurate Rigid foam (PUR), Expanded Polystyrene (EPS) and phenolic foam. For both retrofit of existing housing and new builds, an estimate of the share that each of the five conventional products occupy on the market has been produced on the basis of accessible research (AMA Research 2015; INCA, 2015; OFT, 2012a) and conversations with local suppliers and installers. 10% of the supply has been removed to account for other types of products, for example, extruded polystyrene or recycled plastic fibres.

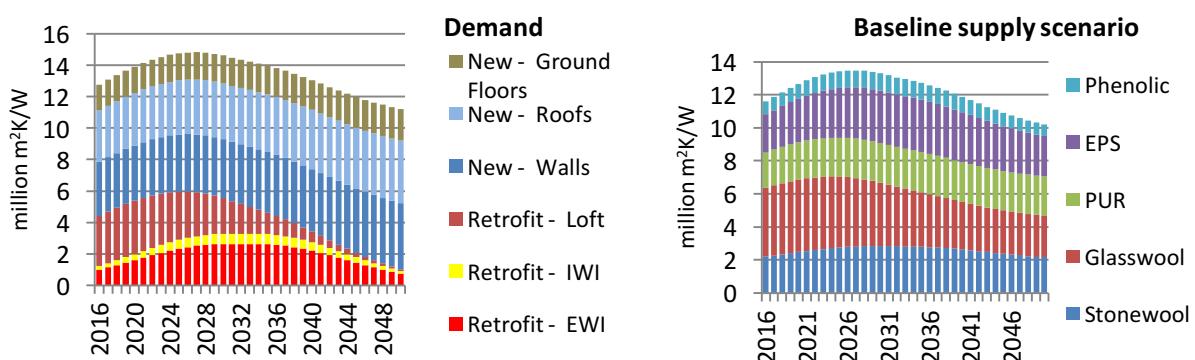


Figure 1. Forecasted demand for insulation products in Wales by envelope type (on the left), and baseline ‘business as usual’ supply scenario by product type (on the right).

Three alternative scenarios are investigated for the potential to substitute conventional fossil- and mineral-based products with biomass-based ones. Each of the three alternative scenarios includes one biomass-based type: sheep wool, hemp fibre and Low-Density (LD) wood fibre. As these are “soft” fibrous products which do not resist compression, they need to be encased in a structural frame. Thus for all envelope types (except loft) it is necessary to include a layer of High Density (HD) wood fibre to provide homogeneity of the U-value across the envelope area. A HD wood fibre layer has been included in the calculations, constituting 33% of the material of EWI and IWI retrofit applications, and 17%, 16% and 19% in external walls, roofs and ground floors of new dwellings.

The introduction of biomass-based products is modelled by progressively increasing their share of the market each year (at the expense of the conventional products) following an “S” curve, which starts at 0% in 2016 and reaches its maximum in 2040. For each of the three alternative scenarios, four levels of substitution are modelled: from “small”, reaching a maximum of 25% of the market in 2040, to “very large”, reaching 100% of the market. The level of substitution determines the amount of baseline products which are substituted with biomass-based ones. Table 1 shows the total share of baseline products remaining in the alternative scenarios after the substitution, i.e. the amount of conventional products which are not replaced with biomass-based ones.

Table 1. Maximum substitution reached and share of remaining baseline

Level of substitution	Small	Medium	Large	Very large
Maximum substitution reached	25%	50%	75%	100%
Total share of remaining baseline	85.6%	72%	58.8%	45.5%

Once the amount of each product in the baseline and alternative scenarios is quantified in  $\text{m}^2\text{K/W}$ , the EEI of each scenario can be estimated by scaling up the impact values calculated on the basis of a functional unit of  $1 \text{ m}^2\text{K/W}$ . These values are taken from published cradle-to-gate LCA for each product type and consider five impact categories: Primary Energy Use (PEU, in MJ), Global Warming Potential (GWP, in  $\text{kgCO}_2\text{eq}$ ), Acidification Potential (AP, in  $\text{kgSO}_2\text{eq}$ ), Eutrophication Potential (EP, in  $\text{kgPO}_4\text{eq}$ ), and Photochemical Ozone Creation Potential (POCP, in kg ethene-eq). Higher and lower values of EEI are produced to provide a range of variations around the main LCA results.

For sheep wool and hemp fibre, the LCAs use detailed inventories given in Norton (2008) with modifications to model local manufacture and economic allocation, with data from Williams et al. (2006) for the EEI of sheep raising. A sensitivity analysis is performed on the economic allocation to obtain values of higher and lower EEI. For the conventional products and wood fibre, LCA values are obtained using either aggregated inventories found in the GaBi Professional database or recent Environmental Product Declarations (EPD) when GaBi data is not available. Existing LCA studies are used to benchmark the impact of these products against the available literature, and to provide values of higher and lower EEI.

The requirements for biomass-based products generated by the alternative supply scenarios are translated into demand for natural resources, and compared to indicators related to the capacity of the Welsh territory and economy to supply such resources. The requirement for sheep wool insulation is translated into demand for raw sheep wool and compared to the amount produced in Wales yearly, while the requirement for hemp fibre insulation is translated into demand for agricultural land and compared to the area of land cultivated in Wales with similar crops. Both comparisons are based on figures from Welsh agricultural statistics (Welsh Government, 2016). The requirement for LD and HD wood fibre insulation is translated into demand for softwood chips, and compared to the potential availability of this material in Wales. This is estimated by taking the forecasted availability of softwood in Wales (Forestry Commission, 2015) and assuming that 35% of the timber is ultimately sold as chips to wood processing industries, which is based on historical figures for softwood production and consumption in Wales (Forestry Commission, 2015).

The market price of insulation products have been collected through a desktop-based survey of prices in UK as indicated on the websites of UK retailers in February 2017 (VAT and shipping excluded). Data such as thickness, weight, and thermal conductivity have been recorded for each product, and the price converted in  $\text{£}/\text{m}^2/\text{W}$ , allowing a comparison between products on the basis of equal thermal resistance. The dataset of prices (168 entries) is used to estimate an average price for each product type and identify a range of maximum and minimum values, although caution is taken in the analysis, as the survey could not rely on a fully representative sample of the UK insulation market.

## Results and discussion

Following the objectives stated in the introduction, the results are divided in three parts: 1) an analysis of the changes in EEI brought by the alternative supply scenarios; 2) a comparison between the demand for biomass-based products and the potential supply capacity of Wales; 3) an overview of the current market prices for insulation.

### **Embodied environmental impact**

The EEI of the three alternative scenarios is presented as percentage of the EEI of the baseline scenario, considered equal to 100. Figure 2 illustrates the change in each EEI category when the alternative scenarios reach 50% of maximum substitution. Figure 3 shows the overall change in EEI (five categories combined into a single score) achieved by varying the level of substitution of conventional with biomass-based products. The single score is obtained by normalising the EEI values and summing the results without applying a weighting factor. In Figure 2 and Figure 3 the range associated to each biomass-based product represents the potential best and worst cases, calculated by giving higher EEI values to conventional products and lower EEI values to biomass-based ones, and vice-versa. These ranges allow considering the potential magnitude of variation that might occur between the EEI of insulation products.

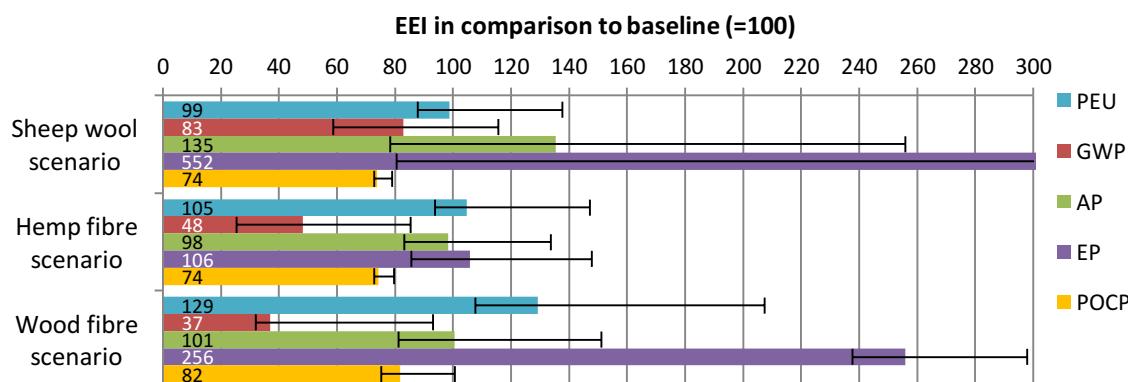


Figure 2. Comparison with baseline EEI, alternative scenarios with “medium” level of substitution (max. 50%).



Figure 3. Comparison with baseline EEI score, alternative scenarios from “small” level of substitution (max. 25%) to “very large” (max. 100%)

Substituting conventional products with sheep wool is shown to decrease GWP and POCP while increasing AP and EP significantly (Figure 2). The high EP of sheep wool insulation is due to only 2% of the EEI of sheep raising being economically allocated to the insulation product. However, EP is the least significant EEI category once values are normalised, which limits the effect that high EP value of the sheep wool scenario has on its EEI score. Nonetheless, Figure 3 shows that increasing the level of substitution in the sheep wool scenario increases the score up to 10% more than the baseline. Substituting conventional products with hemp fibre is shown to decrease GWP and POCP while slightly

increasing PEU and EP. Increasing the level of substitution in the hemp fibre scenario brings a reduction of up to 40% less than the baseline EEI score. Substituting conventional products with wood fibre decreases GWP and POCP, while increasing PEU and POCP significantly more than hemp fibre. For this reason, increasing the level of substitution in the wood fibre scenario brings a smaller reduction of up to 35% less than the baseline EEI score.

The magnitude of potential variations in EEI, shown by the ranges in Figures 2 and 3, are the highest in the sheep wool scenario. This highlights the effect that increasing or decreasing the fraction of the EEI of sheep raising allocated to the insulation product has on the EEI of the product. If raw wool is considered fully as a by-product of the sheep meat sector by excluding allocation, the EEI of the sheep wool scenario is significantly reduced.

Overall, results indicate that the hemp fibre scenario has the potential to achieve the largest improvement of the EEI when compared to the other alternative scenarios. Large reductions are found for GWP and POCP, with small increases for PEU and EP.

### **Demand for biomass**

Figure 4 shows the demand for raw wool generated by the sheep wool scenario in comparison to historical minimum and maximum annual production in Wales during the years 2005-2014. Demand for raw wool as an insulation product would take up a significant part, if not all, of local production, and it might not be possible to fully supply the “large” and “very large” levels of substitution using only local resources.

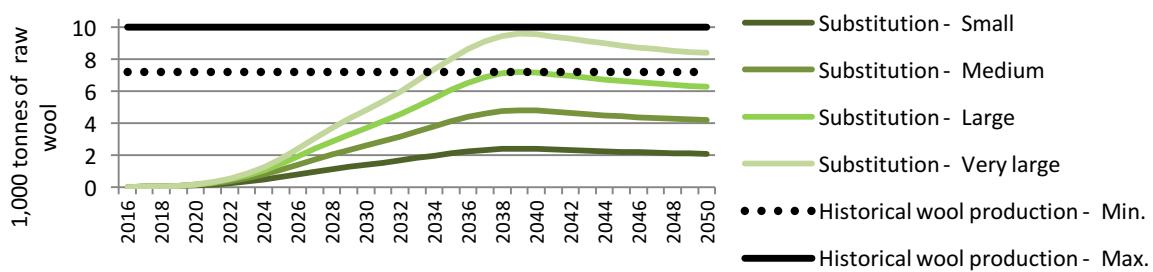


Figure 4. Demand and potential supply for raw wool in the sheep wool scenario

Figure 5 shows the demand for industrial hemp crop generated by the hemp fibre scenarios in comparison to historical minimum and maximum annual use of agricultural land for comparable crops (such as flax and linseed) in Wales during the years 1998-2015. Although it appears that the demand for hemp crop would require a large part of this land and possibly more, it should be considered that these comparable crops occupy only between 2% and 6% of the average land for arable crops in Wales, and only between 0.08% and 0.22% of the area of Wales. Current land used for comparable crops should not be seen as a fixed constraint, as the amount of land used for agriculture is not constant but changes significantly over time, and industrial hemp, being a very resistant crop, could also be grown on marginal land.

The demand and potential supply of softwood chips for LD and HD insulation products are shown in Figure 6. The demand for chips generated by the wood fibre scenario is presented as a percentage (on the right axis) of the forecasted availability of softwood chips from Welsh mills sold to wood processing industries, shown in light blue bars (in absolute units, on the left axis). At the maximum, the demand for chips for insulation would take less than 14% of the potential supply.

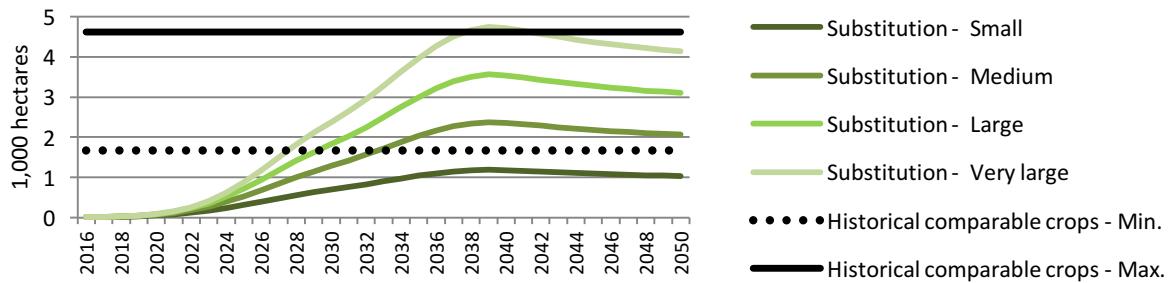


Figure 5. Demand and potential supply for industrial hemp crop in the hemp fibre scenario

Demand and price of wood chips have been rising in recent years as a consequence of the increase in the use of biomass for heat (John Clegg Consulting, 2010) and if this trend continues, a higher cost of the primary material might provide an obstacle to the large scale uptake of wood fibre as insulation, which could also impact on all biomass-based products if used in combination with HD wood fibre. The requirements for HD wood fibre as part of the sheep wool and hemp fibre scenarios would generate about a quarter of the demand shown in Figure 6, with a maximum demand of 4% of the potential supply.

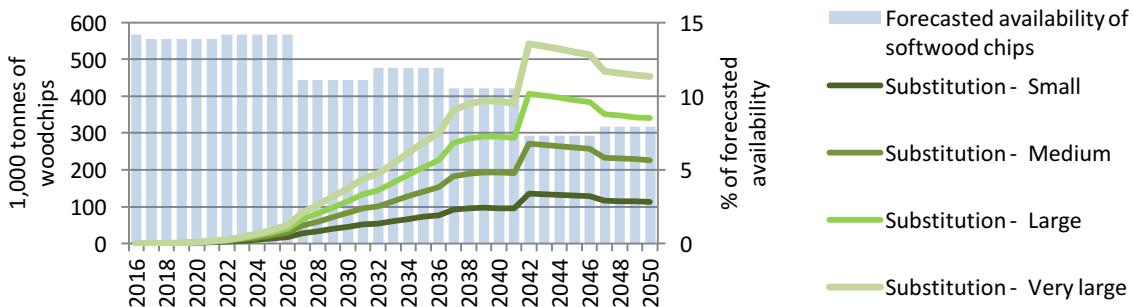


Figure 6. Demand and potential supply for softwood chips in the wood fibre scenario

### **Prices of insulation products**

Figure 7 shows the results of the survey on product prices. For each product type, minimum, average and maximum values are given. Overall, glass wool is the least expensive and HD wood fibre is the most expensive product. Sheep wool is the least expensive biomass-based product, although the difference between the “soft” biomass-based products is small. Overall, biomass-based products can be economically competitive with the more expensive conventional products such as PUR and phenolic foams (though a thicker layer is required), but not with well-established ones such as EPS, stone and glass wool.



Figure 7. Comparison of market prices for insulation products in UK

## Conclusions

The results of the scenarios indicate that among biomass-based insulation products, hemp fibre (in combination with HD wood fibre) could be the best option to improve the EEI of the future supply of insulation in Wales. The demand for hemp fibre could be sustained with locally-grown industrial hemp using less than 5,000 hectares of land, while the demand for wood fibre could be met with softwood chips from Welsh mills. However, current market prices do not make biomass-based products competitive with conventional ones. To enable a larger uptake of biomass-based products, prices could be reduced through savings in the costs of materials and/or manufacture (due to technical improvement or the effects of economies of scale) or through a financial incentive reflecting the EEI of products, which could be based on EPD certificates.

## References

- Allen, A. (2016). The Enormous Potential of Industrial Hemp. *The Solutions Journal*, 7(2), 36-39
- AMA Research (2015). *Building insulation products market report UK – 2015-2019 analysis*. 6th edition, October 2015. Cheltenam, UK: AMA Research Ltd
- Asdrubali, F., D'Alessandro, F. and Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, 4, 1–17
- Carus, M., Karst, S. and Kauffmann, A. (2013). *The European Hemp Industry: Cultivation , processing and applications for fibres, shivs and seeds*. Huerth, Germany: European Hemp Industry Association
- Forestry Commission (2015). *Forestry Statistics 2015*. Edinburgh, UK: Economics and Statistics, Forestry Commission
- Hayward, C., Matthews, N. and Morton, G. (2013). *WRAP Business Development Support (BDS) - Project Report for Recovery Insulation Ltd*. Didcot, UK: Ricardo AEA.
- Insulated Render and Cladding Association (INCA, 2015). *Market data 2014*. London, UK: INCA
- John Clegg Consulting (2010). *Wood fibre availability & demand in Britain 2007-2025*. Edinburgh, UK: John Clegg Consulting Ltd
- Norton, A.J. (2008). *The Life Cycle Assessment and Moisture Sorption Characteristics of Natural Fibre Thermal Insulation Materials*. PhD. Bangor University.
- Office for Fair Trading (OFT, 2012a). *Home insulation - A report on the Call for Evidence carried out by the OFT*. London, UK: OFT.
- Office for National Statistics (ONS, 2014). *National Energy Efficiency Data-Framework (NEED): anonymised data 2014*. London, UK: ONS
- Patterson, J.L. (2016). Evaluation of a Regional Retrofit Programme to Upgrade Existing Housing Stock to Reduce Carbon Emissions, Fuel Poverty and Support the Local Supply Chain. *Sustainability* 8(12), 1261
- Varriale, F. (2016). Forecasting future demand for domestic thermal insulation in Wales. *Indoor and Built Environment*, 25(7), 1096-1113
- Welsh Government (WG, 2013). *Living in Wales Household Survey 2008*. Cardiff, UK: WG.
- WG (2014a). *Dwelling stock estimates for Wales, 2012-2013*. Cardiff, UK: WG
- WG(2014b). *The Building Regulations 2010 – Conservation of Fuel and Power – Approved Document L1A*. Cardiff, UK: WG
- WG(2016). *Welsh Agricultural Statistics*. Cardiff, UK: Welsh Government
- Williams, A.G., Audsley, E. and Sandars, D.L. (2006).*Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities*. Main Report. Defra Research Project IS0205. Bedford: Cranfield University and Defra.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## Life cycle assessment of prefabricated timber frame ‘open-renovation-systems’ for rooftop extensions

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**Abstract:** Compact building design is a key challenge in Flanders. Additional housing is required due to the growing Flemish population combined with decreasing household size. Seen the current problems of urban sprawl, densification of the current residential area offers a solution to address these extra housing needs and to avoid further fragmentation of remaining valuable open space. Therefore, the emphasis in this research is on designing and evaluating affordable and innovative ‘open-renovation-systems’ for low-energy rooftop extensions on residential buildings. In preliminary research, a screening of a current Belgian timber frame system for a rooftop extension has been made at both the element and building level through a life cycle assessment. The wooden based parts of the timber frame were identified as hotspots. This paper builds further on these results and focuses on how to reduce the environmental impact of prefabricated timber frame renovation systems. The results of this paper show that optimizing the wooden sections in timber frame walls by means of using I-joists instead of solid studs can slightly reduce the environmental impact. Furthermore, this study confirmed that the modelling of the wood preservatives has an important influence on the results and hence a correct modelling is necessary.

**Keywords:** Life Cycle Assessment (LCA), environmental impact, timber frame, rooftop extensions

### Introduction

Compact building design is one of the current key challenges in Flanders. Despite a high population density, the density measured within the residential area of Flanders is very low compared to other European countries (Eurostat, 2012). Moreover, due to the growing Flemish population combined with decreasing household size, additional housing is still required (Ryckewaert et al., 2011). Densification of the current built-up area offers a solution to address these housing needs without further fragmentation of remaining valuable open space.

This paper is part of an ongoing research which deals with the aforementioned issues and focuses on designing and evaluating prefabricated timber frame systems for rooftop extensions on residential buildings. The choice for prefabricated timber frame systems is based on the key requirements of minimal disturbance for the neighbourhood and inhabitants and of not overloading the existing structure including foundations (i.e. need for a lightweight structure). In a preliminary research step (Wijnants et al., 2016) a Belgian rooftop extension in timber frame has been analysed over a lifespan of 60 year. The timber and timber-based parts in the timber frame wall were identified as the parts with the highest environmental impact of the considered timber frame wall. This high impact is mainly due to the end-of-life (EOL) processes of these parts. Analysis of the generic datasets used for the

end-of-life processes of treated wood learned that it includes chromium. Chromium is however no longer used in Belgium as preservation for construction wood. As untreated wood had a 50% lower environmental impact than treated wood, further research on the current wood preservation used in Belgium was needed.

The humidity, temperature and climate variations are the primary factors affecting the risk of wood degradation. (NBN EN 335, 2013) Depending on the type and duration of exposure to these factors and the possibility of drying of the timber, five use classes are distinguished. Construction wood is classified in use class 2. The wood in this use class is wood not in contact with soil and normally not exposed to weather influences nor to leaching. A temporary wetting is however possible. (NBN EN 335, 2013) This means that insects and moisture are possible threats for the wood and wood preservation is often necessary.

There are no mandatory Belgian standards regarding wood preservation in the private sector, but technical specifications are elaborated after a broad consultation of a wide range of major actors in the sector and are considered as “good practice” to be followed by architects and contractors. These technical specifications are published in STS 04.03 (Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009).

In Belgium, wood preservation based on immersion process ‘A2.1/T3: behandeling door lange drenking’ is currently most common for timber frame constructions (Dobbels, 2016; Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009). This treatment involves submerging of wood into a dipping tank filled with wood preservative for a period of at least one hour (Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009).

The main aim of this paper is twofold. Firstly, the environmental impact calculations of an organic solvent based wood preservative for treatment process A2.1/T3 is assessed and described in detail. Secondly, the potential environmental impact reduction by means of changing the type and dimensions of the timber frame studs is analysed.

## Methodology

The assessment of the life cycle environmental impact of timber frame elements is based on the Belgian MMG Life Cycle Assessment (LCA) method (Allacker et al., 2013). The MMG method follows an integrated life cycle approach, as recommended by the European standards EN 15804+A1 (CEN, 2014) and EN 15978 (CEN, 2011) for the evaluation of construction products and buildings. The entire life cycle of the building is considered, namely initial stage, use stage and end-of-life (EOL) stage. The MMG method includes two sets of impact categories: (1) the ones of the CEN standards (Global warming, Depletion of the stratospheric ozone layer, Acidification of land, Eutrophication freshwater and marine, Photochemical oxidant formation, Abiotic depletion of non-fossil resources, Abiotic depletion of fossil resources) and (2) seven additional impact categories, referred to as CEN+ indicators (Human toxicity, Particulate matter formation, Ionising radiation, Ecotoxicity, Land occupation, Land transformation). The LCA results are expressed in external environmental costs. The environmental impact calculations are based on the generic database Ecoinvent v3.2 (Ecoinvent, 2014), transport and end-of-life processes are adapted to the Belgian context. The operational energy use is estimated based on the Equivalent Degree Days (EDD) method. This method follows a static approach based on average solar radiation data for two characteristic months of the year, i.e. March and December (Diensten voor de programmatie van het wetenschapsbeleid, 1984). An average of 1200 equivalent degree days was determined as an appropriate value for well-insulated residential buildings in Belgium

(Allacker, 2010) and hence this value is used for the energy use estimation. In this study, a condensing gas boiler is considered as energy source for heating. A detailed description of the MMG LCA method can be found in the MMG report (Debacker et al., 2012). At the Architectural Engineering research division of the KU Leuven, the MMG method was translated into a calculation tool which was used for the analysis presented in this paper.

As indicated in the introduction, the environmental cost caused by the common wood preservation treatment in Belgium is still lacking in the current MMG database. Therefore, an organic solvent based wood preservative in accordance with A2.1 processes is modelled and added to the MMG database. The environmental impact due to production of this organic solvent based wood preservative is calculated based on the Ecoinvent record (Ecoinvent centre, 2014) '*Wood preservation, dipping/immersion method, organic solvent based, indoor use, occasionally wet {RER} / wood preservation, dipping/immersion, solvent-based preservative, indoor use, occasionally wet / Alloc Rec, U*'. The wood preservative inventoried in this dataset is an organic solvent-based primer for use class 2 and contains 0,55% Iodopropynyl Butyl Carbamate (IPBC), 0,15% Permethrine and 0,6% Tebuconazole as active agents and a 100% v/v concentration for application. This record is adapted according to the composition of the Belgian wood preservative AXIL MULTI (ATG 12/2294) (Belgische Unie voor technische goedkeuring in de Bouw, 2013). The quantity active agents, expressed in mass fraction, of this wood preservative are: 0,17% Propiconazole, 0,3% Tebuconazole, 0,1% Cypermethrine and 0,3% IPBC. As the production of Propiconazole is not in the Ecoinvent database, Tebuconazole is used as a proxy as both are triazole fungicides (The American Phytopathological Society, 2017). The quantity of active agents in the adapted record is less than in the original Ecoinvent record and therefore the quantity of solvent is also adapted accordingly. The record used covers the impregnation of wood in open tank and considers that the wood preservative penetrates the wood three millimetres with a critical concentrate value of 40 kg/m<sup>3</sup> in this treated zone. The amount of wood preservative in 1 m<sup>2</sup> timber frame wall is hence dependant on the dimensions of the timber frame studs.

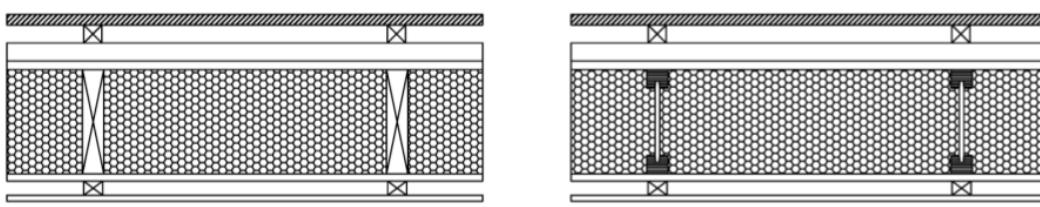
Due to a lack of end-of-life (EOL) processes in Ecoinvent for wood treated with preservatives, an estimation of the environmental impact due to incineration is made based on available data in literature. For the EOL incineration of the organic solvent based treated wood, the emissions to air are calculated based on the constituents of the wood preservative which are added in the production dataset. Based on Salthammer et al. (1995) and Tame et al. (2007), the emissions due to the formation of polychlorinated Dibenz-p-Dioxins (PCDD) and Polychlorinated Dibenzofurans (PCDD/F) are added. The Ecoinvent dataset of untreated wood is used as proxy for landfilling. The EOL scenario of wood is assumed identical to these in the MMG method: 5% of the treated wood is landfilled, 95% is incinerated. Furthermore, in line with the MMG method, it is assumed that the EOL processes occur in Belgium. The energy mixes in the standard Ecoinvent EOL datasets are therefore replaced by their Belgian equivalent. The EOL processes for incineration of laminated timber, oriented strand board (OSB) and wood fibre are currently lacking in the Ecoinvent database. An estimation of their environmental impact is based on the required amount of glue during production and on available data in literature (Moreno et al., 2017; Risholm-Sundman and Vestin, 2005). Pollution due to the emission of nitrogen oxide and formaldehyde are considered. The same assumptions are made as described above for the EOL of organic solvent based treated wood.

## Results

A timber frame wall with different stud types and dimensions has been analysed over a lifespan of 60 year to assess the potential environmental impact reduction by optimizing its bearing structure. The composition of the analysed timber frame wall element is described in Table 1. The internal and external finishes are assumed identical in all cases, the dimensions of the timber frame and insulation between the timber studs differ in all cases considered. The composition of the wall with solid studs of 14,5 cm slightly differs in order to fulfil the current Energy Performance (EPB) requirements in Belgium. Two possible solutions are analysed. In the first solution, the wood fibre board has a thickness of 40 mm instead of 18 mm. In the second solution, an extra insulation layer of 60 mm in XPS and a damp open foil is added. The U-value of the latter solution is identical to the U-value of a timber frame wall with solid studs of 24,5 cm. Solid wooden studs are compared with I-joists consisting of laminated veneer lumber flanges and a web with a thickness of 10 mm in OSB. The analysed dimensions of the studs as well as their U-value are provided in Figure 1. The dimensions of the solid studs are based on commonly used timber frame kits in Belgium. The dimensions of the I-joists are based on the available dimensions on the market and as close as possible to the dimensions of the solid studs in order to make a useful comparison between both. The environmental cost is expressed in euro per m<sup>2</sup> timber frame element.

Table 1. Overview of the wall compositions analysed

<b>Timber frame wall</b>
External finishes - wooden claddings - larch (thickness 22 mm) - ventilated cavity
External finishes - support structure for wooden claddings - wood Belgian mix - 38 x 38 mm - each 600 mm
External finishes - XPS (only for stud 14,5 cm (XPS)) - 60 mm
External finishes - wood fibre board - 18 mm (except for stud 14,5 cm (WFB): thickness 40 mm)
Thermal insulation between timber frame - glass wool
Timber frame
Internal finishes - OSB board - 15 mm
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm
Internal finishes - gypsum board - 12,5 mm - screwed - width 600 mm
Internal finishes - painting on gypsum board - acrylic paint



- |  |   |
|--|---|
| Solid stud 4,5*14,5cm WFB (U-value: 0,24 W/m <sup>2</sup> K) | I-joist 4,5*16cm (U-value: 0,22 W/m <sup>2</sup> K) |
| Solid stud 4,5*14,5cm XPS (U-value: 0,18 W/m <sup>2</sup> K) | I-joist 4,5*20cm (U-value: 0,18 W/m <sup>2</sup> K) |
| Solid stud 4,5*19,5cm (U-value: 0,22 W/m <sup>2</sup> K)     | I-joist 4,5*24cm (U-value: 0,15 W/m <sup>2</sup> K) |
| Solid stud 4,5*24,5cm (U-value: 0,18 W/m <sup>2</sup> K)     |   |

Figure 1. Description of the timber frame compositions analysed

The life cycle environmental cost of the seven timber frame variants analysed is shown in Figure 2. The walls composed of wooden studs of 19,5 cm and 24,5 cm have an equal impact regarding material use than their equivalent timber frame walls composed of I-joists. The timber frame walls composed of solid studs of 14,5 cm have a 3% higher impact than their equivalent I-joist and an equal material use impact than the wall composed of solid studs of

19,5 cm. These higher material impacts are due to the impact of the thicker wood fibre board or extra XPS board in order to fulfil the current EPB requirements in Belgium, as described above. The environmental impact due to operational energy use is lower for the I-joists, compared to their equivalent solid studs, respectively 8%, 17% and 15% lower. On the contrary, the solution composed of solid studs of 14,5 cm and an extra XPS board has a 17% lower impact than its equivalent wall with I-joists. The life cycle environmental costs of the walls composed of I-joists is 5% - 6% lower compared to the walls with solid studs, except when compared to the solid stud with XPS insulation (i.e. the I-joist solution has a 4% higher life cycle environmental cost). Comparing both solutions of the wall composed of studs of 14,5 cm, the extra insulation layer of XPS is environmentally preferable. Compared with the solid wall studs of 24,5 cm which has the same U-value, the solution with XPS is preferable due to a lower material impact. Besides, the latter solution results in 4 cm thinner wall.

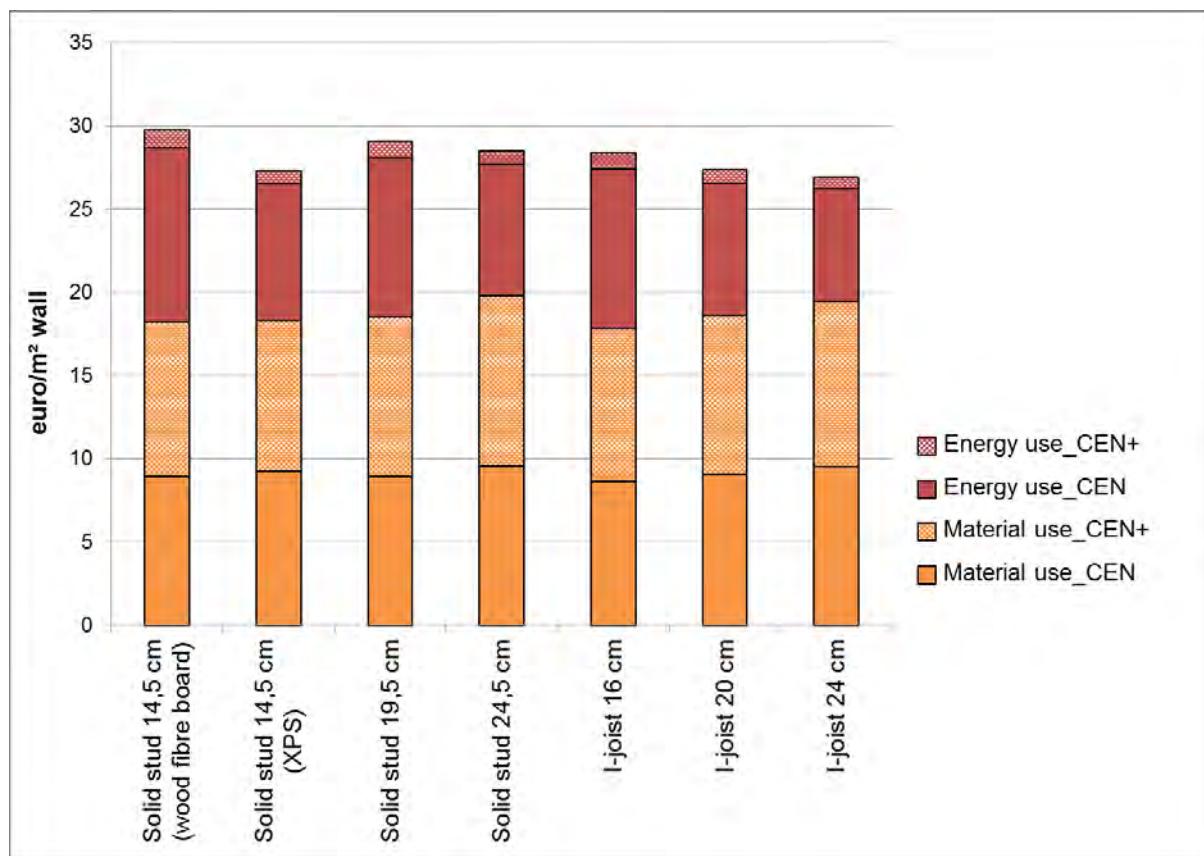


Figure 2. Environmental Life Cycle Cost, subdivided in material use and energy use, expressed in euro/m<sup>2</sup> wall

Moreover, Figure 2 shows that using solid studs or I-joists of respectively 24,5 cm and 24 cm instead of 19,5 cm and 20 cm does not generate a high environmental impact reduction. The environmental life cycle impact of the wall with the I-joists of 24 cm is only slightly (2%) lower than the wall composed of I-joists of 20 cm. However, using insulation materials with a different thermal conductivity may lead to other conclusions. In the subsequent paragraphs, a detailed comparison between the environmental impact of timber frame walls composed of solid studs and I-joists is made based on solid studs of 19,5 cm and I-joists of 20 cm.

Figure 3 shows the environmental impact per life cycle phase. As described above, the environmental cost for the operational energy use is 17% lower in case of a timber frame wall composed of I-joist. This is due to the higher insulation fraction and lower wood fraction. The

other life cycle phases have an equal environmental impact in both wall compositions. Figure 4 shows the environmental cost per life cycle phase, but considers only 1 m<sup>2</sup> of wooden framework (not the complete wall composition). Despite a lower (11%) production impact for I-joists, the EOL cost is only 5% lower for the I-joist. This is due to the higher impact of municipal incineration due to the glue in the laminated timber flanges and OSB web of the I-joists. The environmental impact for waste transport is 35% lower for I-joists, due to a lower amount of wood that has to be transported to waste disposal.

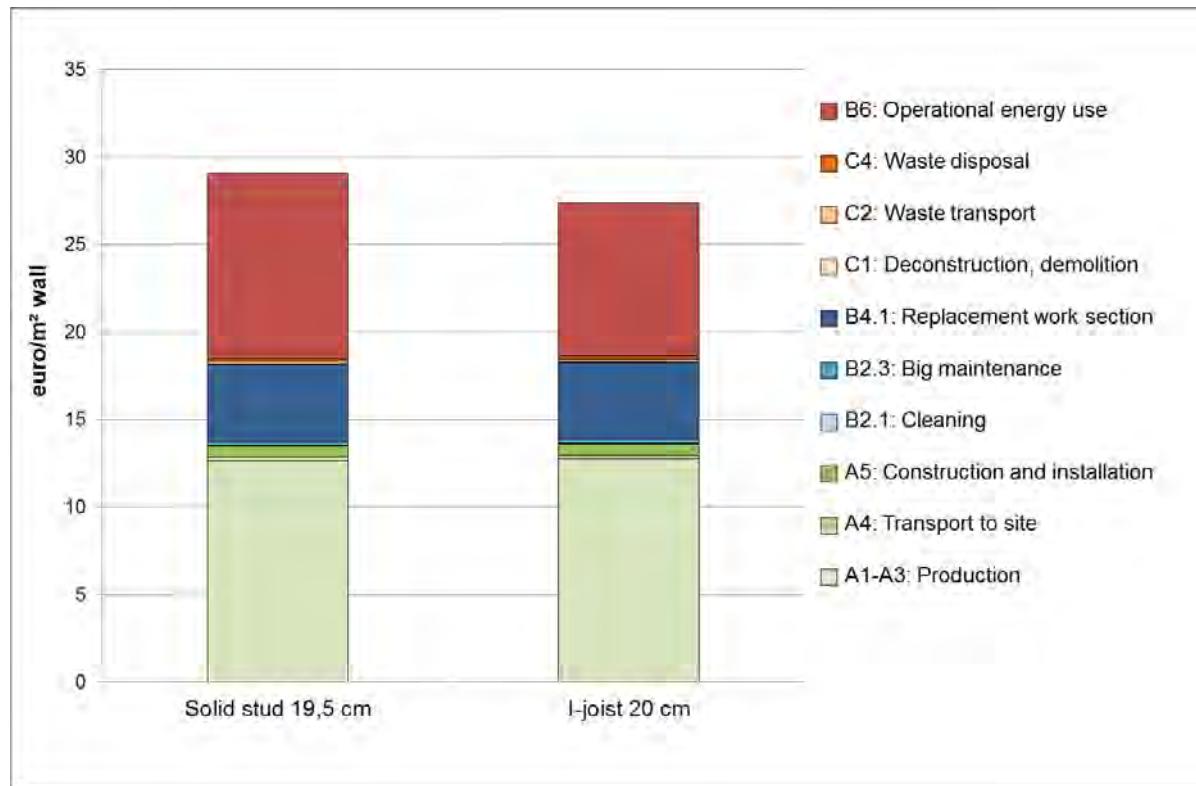


Figure 3. Environmental Life Cycle Cost of a timber frame wall with solid studs of 4,5\*19,5cm (left), and a timber frame wall with I-joists of 4,5\*20cm (right), subdivided per life cycle phase, expressed in euro/m<sup>2</sup> wall

In Figure 5 the environmental impact per work section is provided. In both cases, the wood fibre board has the highest environmental life cycle cost, namely 31% of the total life cycle cost. In case of a timber frame construction composed of I-joists of 19,5 cm, the insulation has a 16% higher environmental cost. Despite the 12% lower life cycle cost of the timber frame composed of I-joists, the total material life cycle cost is equal in both cases due to the higher amount of insulation material in the timber frame composed of I-joists.

Furthermore, this study confirmed that using the existing MMG records for treated wood which are based on chromium preserved wood leads to an overestimation of the environmental impact. The modelled organic solvent based treated wood in this study has only a 6% higher cost than untreated wood, while the chromium preserved wood has a 105% higher environmental cost than untreated wood. Changing the wooden sections in timber frame walls can slightly reduce the total environmental impact up to 10% in the cases considered.

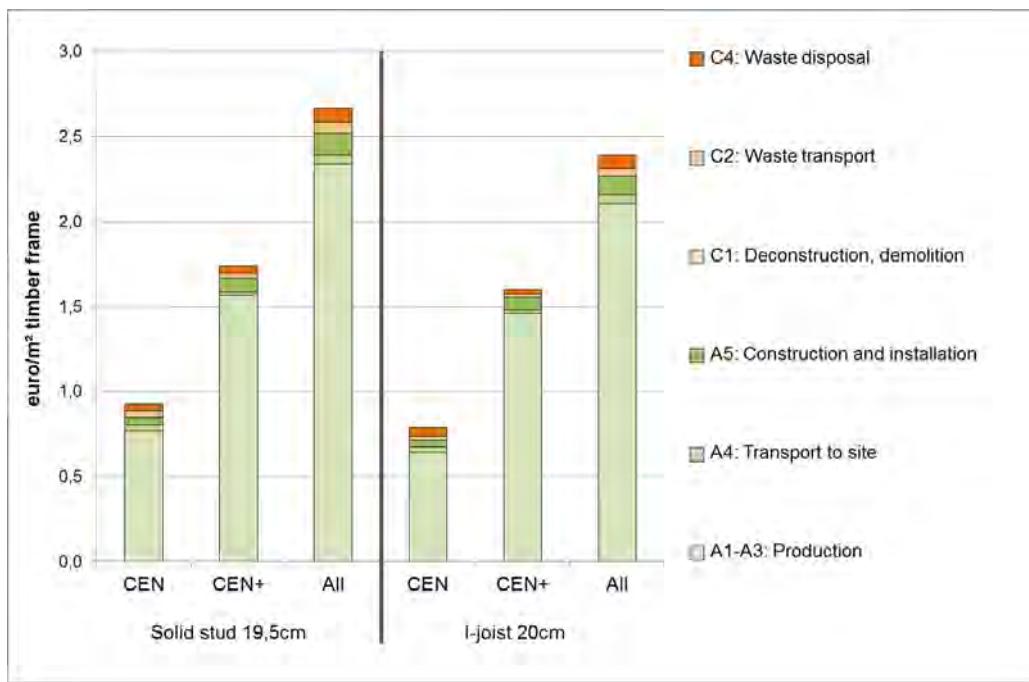


Figure 4. Environmental Life Cycle Cost of 1m<sup>2</sup> timber frame with solid studs of 4,5\*19,5cm (left), and a timber frame with I-joists of 4,5\*20cm (right), subdivided per life cycle phase, expressed in euro/m<sup>2</sup> timber frame

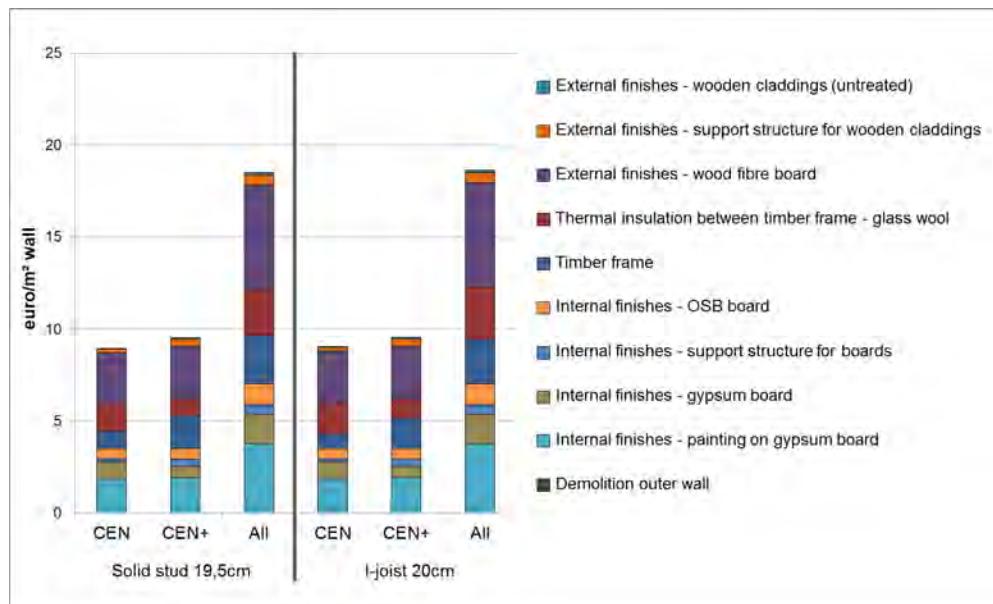


Figure 5. Environmental Life Cycle Cost of a timber frame wall with solid studs of 4,5\*19,5cm (left), and a timber frame wall with I-joists of 4,5\*20cm (right), subdivided per work section, expressed in euro/m<sup>2</sup> wall

## Conclusion and recommendations

In this paper, two aspects in evaluating and optimizing the environmental cost of timber frame systems is analysed. Firstly, the environmental impact calculations of a commonly used organic solvent based wood preservative in Belgium for treatment process A2.1/T3 is modelled and described in detail. Secondly, the potential environmental impact reduction by means of changing the type and dimensions of the timber frame studs is assessed.

This study confirmed that a correct modelling of the wood preservative is necessary. The Ecoinvent records for treated wood which are based on chromium preserved wood lead

to an overestimation of the environmental impact of more than 100% and should not be used for wood in the Belgian context.

Changing the type and dimensions of a timber frame wall can slightly reduce the total environmental impact up to 10% in the cases considered. Of the cases considered, a timber frame wall composed of I-joists of 24 cm is preferable from an environmental perspective. Despite an equal material impact, I-joist are in general preferable compared to solid studs. This is due to the higher share of insulation material for the same wall and thus a lower energy use. Furthermore, a thinner timber frame structure combined with an extra insulation layer has a higher environmental reduction potential than enlarging the dimensions of the studs.

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## References

- Allacker, K., (2010). *Sustainable building, The development of an evaluation method*. PhD. KU Leuven.
- Allacker, K., Debacker, W., Delem, L., De Nocker, L., De Troyer, F., Janssen, A., Peeters, K., Servaes, R., Spirinckx, C., Van Dessel, J., (2013). *Environmental profile of building elements*. Mechelen: OVAM.
- Belgische Unie voor technische goedkeuring in de Bouw. (2013). *Technische Goedkeuring ATG met Certificatie - Procédés voor de preventieve behandeling van het hout - ATG 12/2294 -AXIL MULTI*. Brussel.
- CEN (Ed.), (2014). EN 15804+A1 Sustainability of construction works - Environmental product declaration - Core rules for the product category of construction products.
- CEN (Ed.), (2011). EN 15978 Sustainability assessment of construction works - assessment of environmental performance of buildings - calculation method.
- Debacker, W., Allacker, K., De Troyer, F., Janssen, A., Delem, L., Peeters, K., De Nocker, L., Spirinckx, C., Van Dessel, J., (2012). *Environmental Related Material Performance of Building Elements*. Mechelen: OVAM.
- Diensten voor de programmatie van het wetenschapsbeleid, (1984). *Ontwerp en thermische uitrusting van gebouwen - deel 2* (translated title: Design and technical equipment of buildings - part 2). Brussels.
- Dobbels, F., (2016). Vraag ivm behandeling structureel hout.
- Ecoinvent, (2014). *Ecoinvent* [WWW Document]. URL <http://www.ecoinvent.ch/>
- Eurostat, (2012). *Built-up areas - Eurostat* [WWW Document]. URL [http://ec.europa.eu/eurostat/web/products-datasets/-/t2020\\_rd110](http://ec.europa.eu/eurostat/web/products-datasets/-/t2020_rd110) (accessed 4.13.17).
- Federale overheidsdienst economie, K.M.O., middenstand en energie, (2009). *STS 04 Hout en plaatmaterialen op basis van hout STS 04.3 Behandelingen van hout*. Brussel: Federale overheidsdienst economie, K.M.O., middenstand en energie.
- Moreno, A.I., Font, R., Conesa, J.A., (2017). Combustion of furniture wood waste and solid wood: Kinetic study and evolution of pollutants. *Fuel*, 192, pp. 169–177.
- NBN EN 335, (2013). Durability of wood and wood-based products - Use classes: definitions, application to solid wood and wood-based products. Brussel: Bureau voor Normalisatie.
- Risholm-Sundman, M., Vestin, E., (2005). Emissions during combustion of particleboard and glued veneer. *Holz Als Roh- und Werkstoff*, 63, pp. 179–185.
- Ryckewaert, M., De Decker, P., Winters, S., Vandekerckhove, B., Vastmans, F., Elsinga, M., Heylen, K., (2011). *Een woonmodel in transitie. Toekomstverkenning van het Vlaamse wonen*. AntwerpenApeldoorn: Garant.
- Salthammer, T., Klipp, H., Peek, R.-D., Marutzky, R., (1995). Formation of Polychlorinated Dibenz-P-Dioxins (PCDD) and Polychlorinated Dibenzofurans (PCDF) during the combustion of impregnated wood. *Chemosphere*, 30 (11), pp. 2051–2060.
- Tame, N.W., Dlugogorski, B.Z., Kennedy, E.M., (2007). Formation of Polychlorinated Dibenz-*p*-Dioxins and Polychlorinated Dibenzofurans (PCDD/F) in Fires of Arsenic-Free Treated Wood: Role of Organic Preservatives. *Environmental Science & Technology*, 41, pp. 6425–6432.
- The American Phytopathological Society, (2017). *Group Code - CommonAndTradeFungicides*. [WWW Document]. URL [www.apsnet.org/edcenter/intropp/topics/Documents/CommonAndTradeFungicides.pdf](http://www.apsnet.org/edcenter/intropp/topics/Documents/CommonAndTradeFungicides.pdf)
- Wijnants, L., Allacker, K., De Troyer, F., (2016). Environmental and Financial Life Cycle Assessment of “Open-renovation-systems”: Methodology and Case Study. *Energy Procedia*, 96, pp. 529–539.



# PLEA 2017 EDINBURGH

*Design to Thrive*

## A Case Study on the Relationship between the Distribution of Air Pollutant and Noise from Road Traffic and the Impacts of Building Typology in High Density Urban Context

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**Abstract:** Air pollutant and noise emitted from road traffic are among the main pollutions affecting the environmental quality of cities. This is particularly pertinent in the context of the cities in Asia and other regions where relatively compact urban form as a result of high density urban development exacerbate the negative impacts of the ever-increasing traffic flows. This study examines the distribution of air pollutant and noise as emitted from road traffic in a simulation based study for four representative building typologies in a high density urban setting so as to understand how these two types of pollutions are related to each other and the impacts of different urban planning and architectural design approaches as mitigation strategies. The findings indicate that there is a high correlation between pollutant concentration level and noise level derived from the same linear traffic source in terms of both horizontal distribution at pedestrian height along the road and vertical distribution in front of building façade, though to various extents depending on building typologies examined. The design strategies such as increasing building porosity and setback have different impacts on the two phenomenon. The findings highlight the importance of environmental performance evaluations for urban planning and architectural design proposals especially in the early planning and design stage so as to mitigate the negative impact of air pollution and noise pollution pre-emptively.

**Keywords:** traffic noise, air pollutant dispersion, building typology, urban morphology, high density city

### Introduction

Air pollutant and noise emitted from road traffic are among the main pollutions affecting the environmental quality of cities and the wellbeing of the urban dwellers. Results summarized from previous studies suggest that transport-related outdoor air pollution as a major source of contributor has significant and adverse effects on human health (Krzyzanowski, Kuna-Dibbert, & Schneider, 2005). Exposure to environmental noise, among which road traffic noise is the biggest cause of community noise in most cities, is responsible for a range of negative health effects (WHO, 2011).

This is particularly pertinent in the context of the cities in Asia and other regions where relatively compact urban form as a result of high density urban development exacerbate the negative impacts of the ever-increasing traffic flows. On the one hand, fast urbanization leads to the expansion of road networks to a greater extent in terms of the length and density of roads, and it also leads to the increase of the number of motorized vehicles and traffic flows. The increase of traffic noise and air pollution levels as a results of

the ever-expanding road network are further exacerbated by constant traffic congestions. On the other hand, the increase of urban population density and the associated urban infrastructures lead to higher and higher proportion of urban dwellers more prone to be exposed to both types of pollutions. The compact built environment of high-density urban developments are usually not helpful in facilitating air movement across urban open spaces or shielding traffic noise so as to mitigate the negative impacts of traffic induced noise and air pollutions.

This study examines the distribution of air pollutant and noise as emitted from road traffic in a simulation based study for four representative building typologies in a high density urban setting so as to understand how these two types of pollutions are related to each other and the impacts of different urban planning and architectural design approaches as mitigation strategies.

## Method

A case study approach was adopted to examine one representative urban block typology commonly implemented in high density cities such as Hong Kong and three alternative hypothetical building forms with higher density, each representing the result of an urban design strategy potentially implementable (Yuan et al., 2014).

As shown in Figure 1, the first case is a typical urban block in the high-density district of Mong Kok in Hong Kong with a plot ratio of 8.9, which consists of medium-rise linear slab blocks parallel to the narrow street and podium blocks cascading down towards the centre of the internal courtyard. Case 2, 3 and 4 have higher plot ratio of 14 but with different spatial compositions of the tower and podium: the slab blocks along the street in case 2 are higher with a continuous podium cover the entire site; the slab blocks in case 3 have a 15m setback from the road, resulting greater spacing between the buildings along the street; in case 4 the continuous building blocks break into tower blocks with a gap of 18m between them. The last three cases were created to examining the impact of increasing building height, setback and gap on the dispersion of air pollutant and propagation of noise from the road.

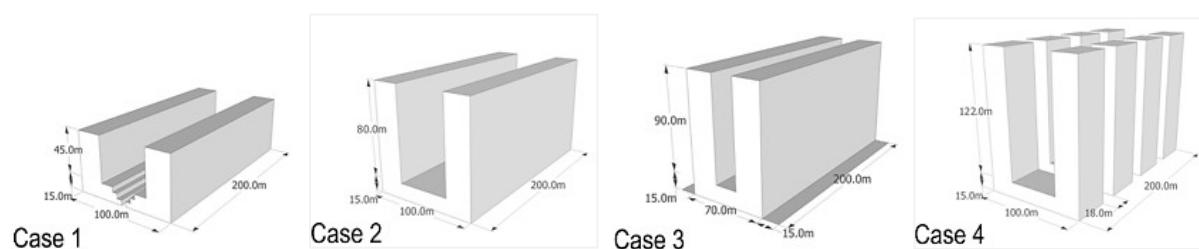


Figure 1. The four urban block cases been examined (Yuan et al., 2014).

As shown in Figure 2, each case was examined in a hypothetical urban context which consists of a 10x6 array of the same type of block in the same spacing between blocks with two more layers of low-rise blocks around the peripheral of the context as the transitional zone between the unbuilt area and the high density area within the computational domain. The purpose is to create a theoretically homogeneous urban context in the same density as the urban block been examined.

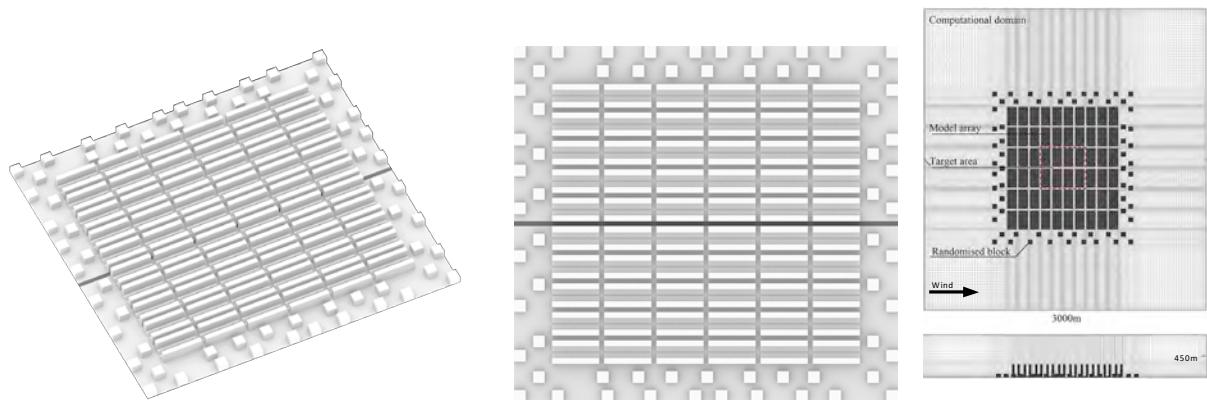


Figure 2. The hypothetical homogenous urban context and the simulation domain (Yuan et al., 2014).

The air pollutant dispersion modelling was conducted by Yuan, et al. (2014), which was validated by cross-comparing modelling results with wind tunnel experiment data from Niigata Institute of Technology (Tominaga and Stathopoulos, 2011). Ethylene ( $C_4H_4$ ) was used as the tracer gas and was released from the point source in the validation study to mimic the wind tunnel experiment. Nitrogen dioxide ( $NO_2$ ) was selected as the emission gas in the parametric study as the traffic emission and was released from a line pollutant source at the bottom of the street canton in the middle of a building gap.

For this study, the traffic noise exposure level as indicated by L10 (18-hour), i.e. the noise level exceeded for 10% of the period from 06:00 to 24:00 according to the CRTN method (Department of Transport Welsh Office, 1988), was simulated in the noise mapping software CadnaA (DataKustik, 2014) with one order of reflection considered. A validation study was conducted previously (Lau, Zhang, Lau, & Lai, 2016) and a strong and positive relationship between the measured and simulated traffic noise exposure levels was identified for measurement points along the road and that in front of the façade facing the road. In this study, the horizontal traffic noise level for outdoor open spaces at 2m height was simulated on a 2x2m grid, and the vertical distribution of traffic noise level in front of building was simulated 2m away along the centres of both the windward and leeward facades along the road.

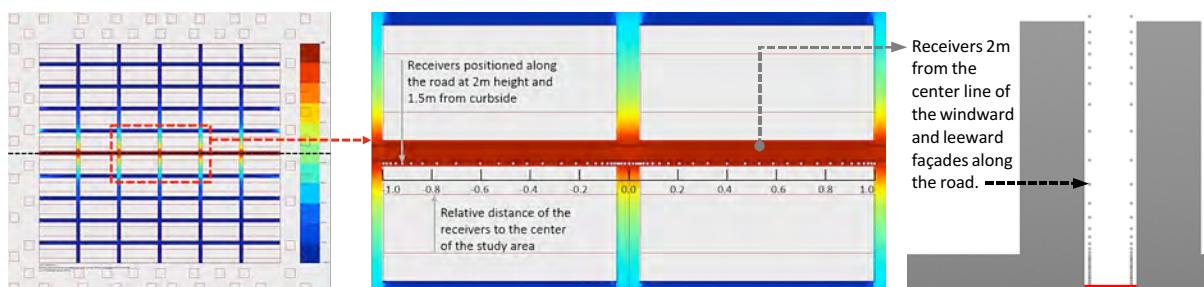


Figure 3. The plan showing the positions of the horizontal receivers above ground along the road and the section showing the vertical receivers in front of building facades.

As shown in Figure 3, the horizontal normalized pollutant concentration level and noise exposure level were extracted from a series of points at 2m height and 1.5m from the curbside of the road. The vertical distributions for both variables were extracted from receiver points in 0.5m interval along the line 1m away from the centre of the windward façade of the centre block in the centre of the domain.

## Results

The simulated normalized pollutant concentration ratio and noise exposure level of L10 (18-hour) on the horizontal grid 2m above ground for the four cases are shown in Figure 4.

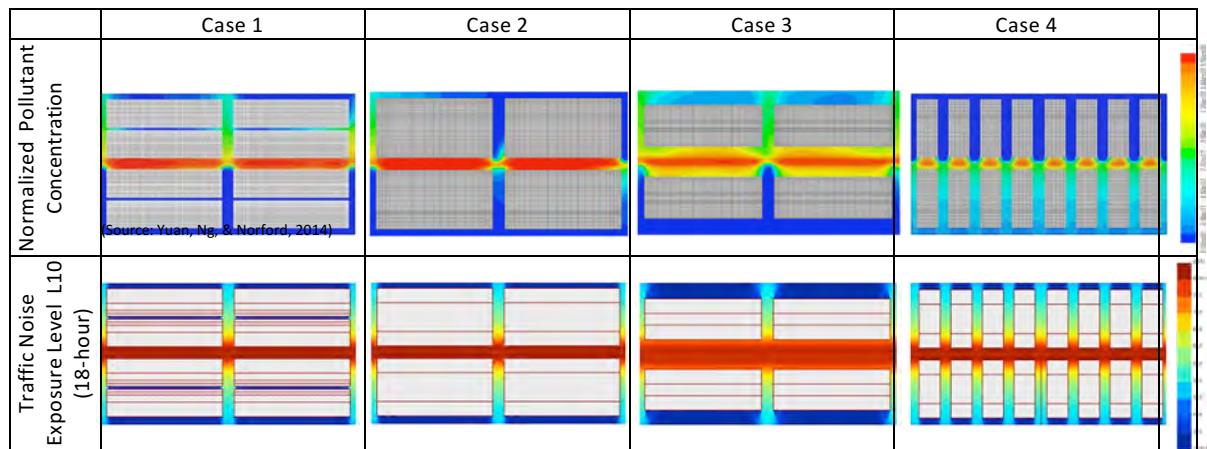


Figure 4. Visualization of the normalized pollutant concentration ratio and noise exposure level on the horizontal grid 2m above ground for the four cases.

As shown in Figure 5, generally speaking, the values for both variables were relatively consistent for the target receivers in front of building façades along the road and both decreased for receivers in front of the gaps between buildings.

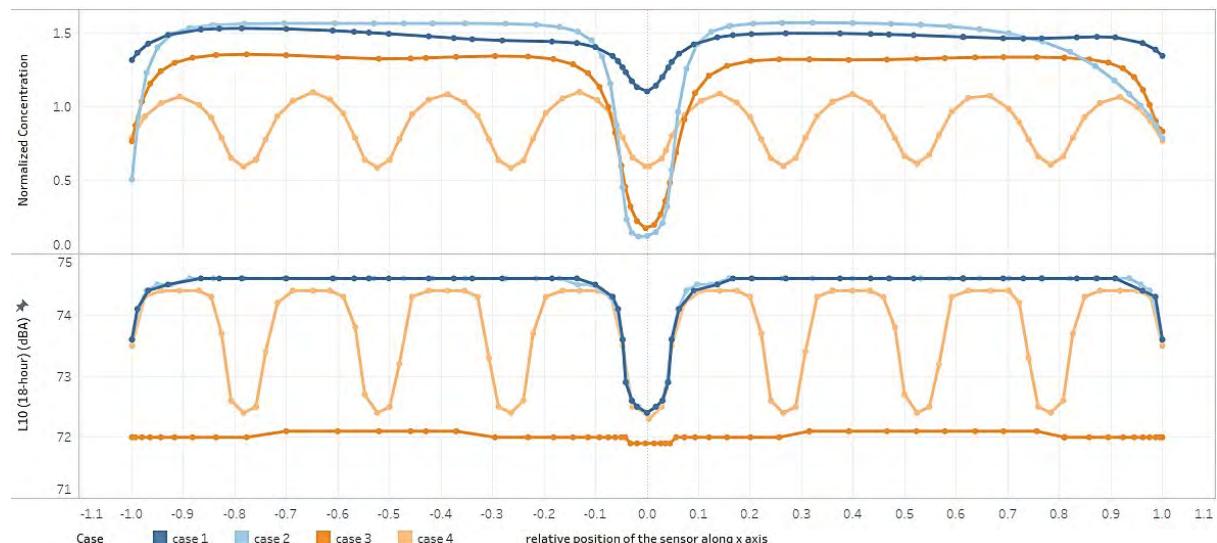


Figure 5. Results of the horizontal distribution of the pollutant concentration ratio and noise exposure level for the four cases.

Regarding pollutant concentration ratio the higher buildings along the road for Case 2 increase the ratio slightly for most of the receivers in front of facades as compared to that for Case 1, and this could probably be attributed to the increased height-to-width ratio of the street canyon. The setback of the buildings for Case 3 leads to the decrease of the ratio for most of the receivers in front of façade as compared to that for Case 2, with slight increase for the receivers in front of the gaps. The additional gaps between buildings for Case 4 effectively reduced the ratio for most of the receivers, and the difference between the ones in front of facades and those in front of gaps was also reduced.

As to the noise exposure level, the difference between Case 1 and Case 2 for most of the receivers are very small, indicating that increase of height-to-width ratio of street canyon may not necessarily lead to higher traffic noise level on ground level along the road. However, the setback of buildings in Case 3 significantly reduced the noise exposure levels for the all the receivers by as much as 2.6 dBA. As compared to Case 1 and 2, adding gaps between buildings like Case 4 also reduced the noise exposure levels for the receivers in front of facades, though to a lesser extent of 2.2 dBA for the ones previously in front of facades and 0.2 dBA for those remaining in front of façade after adding the gaps.

There was a strong correlation between the pollutant concentration ratio and noise exposure level for all the four cases, with the correlation been the highest for Case 4 ( $R^2=0.928$ ), followed by Case 1 ( $R^2=0.914$ ) and Case 2 ( $R^2=0.898$ ). The correlation for Case 3 is relatively the lowest ( $R^2=0.553$ ) due to the significant drop in the noise level and the difference between the receivers.

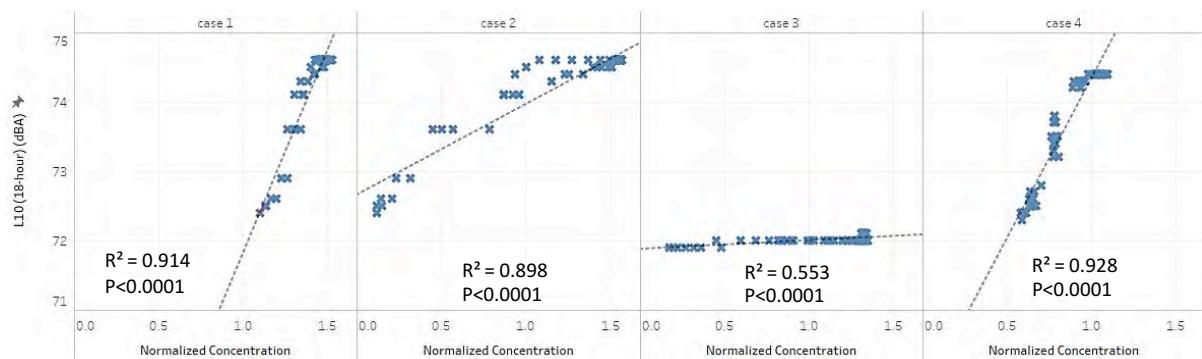


Figure 6. Correlation between pollutant concentration ratio and traffic noise exposure level L10 (18-hour) for the four cases.

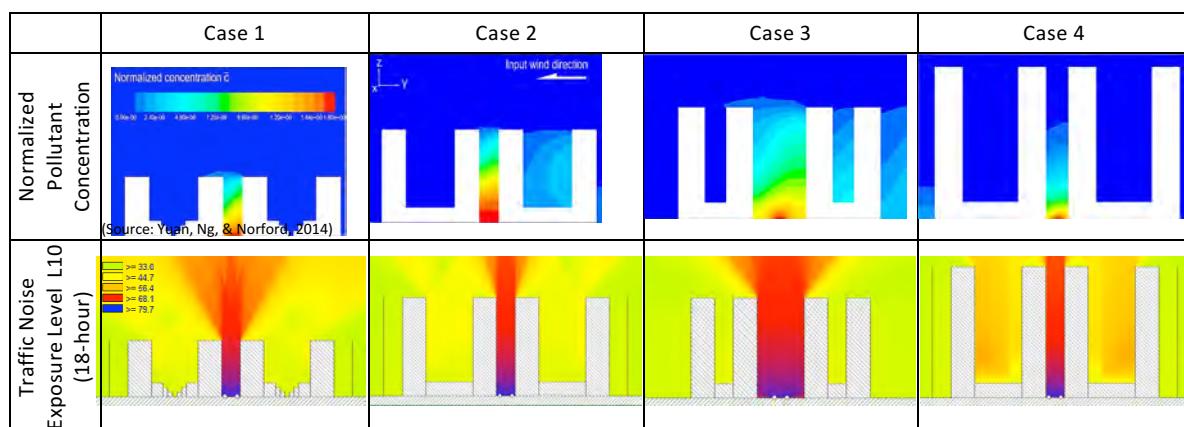


Figure 7. North-south cross sections showing the vertical distribution of the pollutant concentration ratio and traffic noise exposure level L10 (18-hour) for the four cases.

The vertical distribution of the simulated normalized pollutant concentration ratio and noise exposure level of L10 (18-hour) on the section across the blocks close to the centre of the simulation domain are shown in Figure 7.

Generally speaking, as shown in Figure 8, both the pollutant concentration ratio and noise exposure level decreased with increasing height of the receiver, except for Case 3 in which the noise level was the highest for the receiver at the height of 6.6m. The pollutant concentration ratios for the receivers in front of the leeward façade were slightly higher than that for the windward façade at the same reference height. Due to the symmetry of the

source of noise and the physical forms of the cases, the noise exposure levels for the windward and leeward facades are symmetrical.

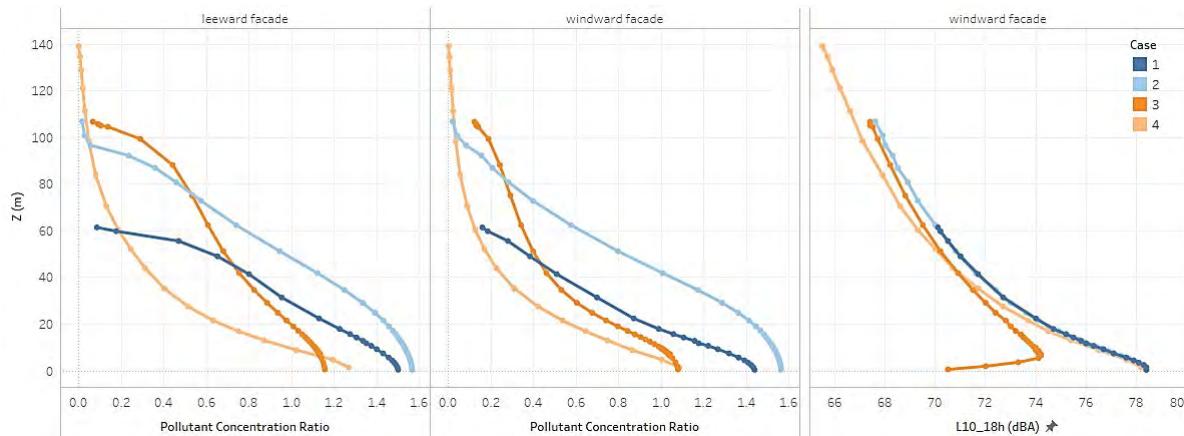


Figure 8. Vertical distribution of the pollutant concentration ratio and traffic noise exposure level L10 (18-hour) for the four cases.

As compared to Case 1, the increase of height-to-width ratio of the street canyon in Case 2 resulted in higher pollutant levels for the receivers in front of both the windward and leeward facades at the same height, and the increase for the windward façade is greater than that for the leeward facade, whereas the noise exposure levels remain relatively the same.

As compared to Case 2, the building setback in Case 3 led to the drop of the pollutant concentration ratio to a level that is even lower than that for Case 1 for the receives up to 40m height. The difference between Case 2 and Case 3 decreases with increasing height up to 75m and 80m for leeward and windward facades, respectively, and the drop is relatively greater for the windward facade. On the other hand, the traffic noise level in front of façade at the same height dropped significantly as compared to that in both Case 1 and Case 2, with the largest decrease been 7.9 dBA at 0.6m height, and the difference decreases with increasing height.

Adding gaps between buildings as in Case 4 results in even greater drop in pollutant concentration ratio as compared to the other three case, with the largest drop of 67% at the height of 27m in front of the windward facade, and the decrease is relatively larger for the windward façade than that for the leeward façade. The gaps between buildings also led to

the drop of noise exposure level, though to a lesser extent, and the drop increases with increasing height.

The strong and positive correlations between pollutant concentration ratio and traffic noise exposure level in front of both the windward and leeward facades for the four cases are illustrated in Figure 9 with the respective R-squared values of polynomial regression analysis indicated, suggesting that the vertical distribution of the two types of pollutions from the same road traffic source within the street canyon are highly correlated with each other.

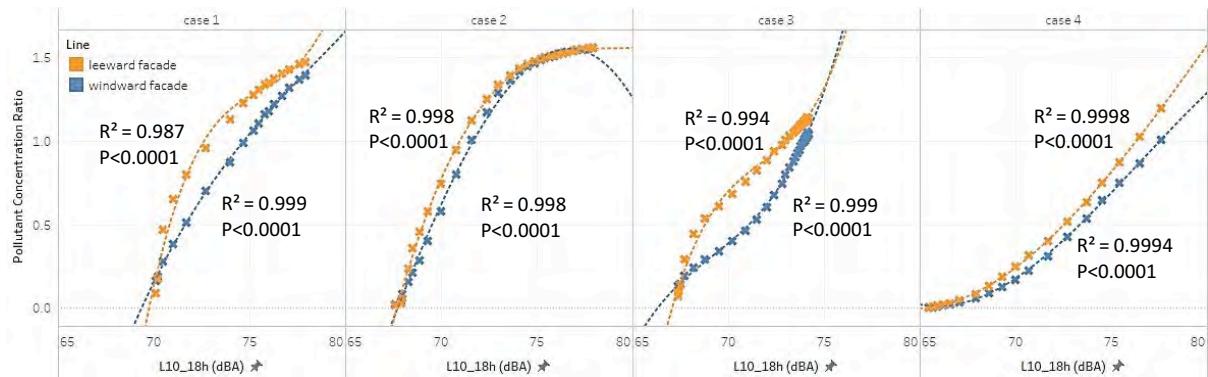


Figure 9. Polynomial regression analysis (3 degrees) between the vertical distributions of L10 (18h) and normalized pollutant ratio for the 4 cases for the receivers above 4m.

## Discussion and Conclusions

The results indicate that the two main types of pollutions emitted from road traffic, air pollutant and traffic noise, are significantly correlated with each other on both ground level along the road and vertically in front of building facades within the street canyon in high-density urban context, though to different extents depending on building typology. Although the accumulation and propagation of air pollutant and traffic noise are different in terms of the underlying physical mechanisms, the strong and positive relationship between them across the representative building typologies examined highlights the importance of studies in approaches from the perspective of urban planning and architectural design approaches that may mitigate both types of traffic pollutions simultaneously.

The findings suggest that different design strategies as investigated through the building typologies examined in this study may have different impacts in terms of mitigating road traffic related air pollution dispersion and noise distribution. In the context of high-density cities, increasing height-to-width ratio of the street canyon may lead to the increase of the concentration of air pollutant both horizontally on ground level along the road and vertically in front of building facades. However, it has no significant impact on traffic noise distribution.

Setback of the buildings from road results in lower air pollutant concentration both horizontally and vertically, and this can probably be attributed to the improvement of outdoor ventilation due to larger distance of façade to the source of noise and larger spacing between buildings across the road. The impact of building setback on noise exposure level is the strongest which leads to drastic drop horizontally and vertically, especially for the lower part of the building façade. This can probably be attributed to the decrease of reflected noise due

to the increase of distance between reflecting façade surfaces. Both increasing height-to-width ratio of the street canyon and building setback benefit the windward façade to a greater extent than the leeward façade.

Increasing the porosity of the urban fabric by creating more gaps between buildings in shorter interval has stronger effect in decreasing reducing air pollution than on lowering traffic noise. The reductions in pollution concentration ratios both horizontally and vertically are the strongest after the increase of gaps between buildings, suggesting the increase of the permeability of urban fabric can effectively facilitate air movement resulting in lower concentration of air pollution. The impact of urban porosity on traffic noise exposure levels is relatively smaller as compared to that of building setback. This is understandable considering that in the setting of this study, traffic noise level of a receiver is primarily determined by its distance to the traffic noise source line and the surrounding

reflecting surfaces.

Further studies are need to include alternative building typologies in different density levels so as to achieve a better understanding of the impact of urban morphology on air pollution dispersion and noise distribution and the deign strategies that can effectively mitigate both types of pollutions in the context of high-density development.

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### References

- DataKustik. (2014). *CadnaA Technical Specifications*. Retrieved from  
Department of Transport Welsh Office. (1988). *Calculation of Road Traffic Noise (CRTN)*.  
Retrieved from  
Krzyzanowski, M., Kuna-Dibbert, B., & Schneider, J. (2005). *Health effects of transport-related air pollution*. Retrieved from [http://www.euro.who.int/data/assets/pdf\\_file/0006/74715/E86650.pdf?ua=1](http://www.euro.who.int/data/assets/pdf_file/0006/74715/E86650.pdf?ua=1)  
Lau, S. S. Y., Zhang, J., Lau, S.-K., & Lai, H. (2016). A Comparative Study of Road Traffic Noise based on Measurement, Prediction and Simulation according to the CRTN Method in Singapore. Paper presented at the the 9th Cross-Straits Acoustic Conference 第九屆海峽兩岸聲學學術交流研討會議-城市噪音污染與人為的聲景格局變化, Macau University of Science and Technology, Macau, China.  
WHO. (2011). *Burden of disease from environmental noise - Quantification of healthy life Years lost in Europe*. Retrieved from [http://www.euro.who.int/data/assets/pdf\\_file/0008/136466/e94888.pdf](http://www.euro.who.int/data/assets/pdf_file/0008/136466/e94888.pdf)  
Yuan, C., Ng, E., & Norford, L. K. (2014). Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. *Building and Environment*, 71, 245-258.

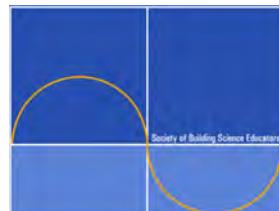
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