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FORWARDS

Housing is a system of energy and environment, yet it fundamentally needs to be designed to accommodate the user needs and demands. They are dynamic having been changed in the course of time. In response to market needs and demands for social, economic and environmental sustainability of housing in developed and developing countries, the zero energy mass custom home (ZEMCH) integrated lean design and construction concept was envisaged and discussed globally. Towards the ZEMCH delivery, an emerging notion of mass customisation was scrutinised initially. It emerged in the same year as the general concept of sustainable development was widespread in 1987. The oxymoron was recognised eventually as a means to lessen housing design and construction costs, whilst achieving the customisability through economies of scope rather than economies of scale.

In order to crystallise a wide spectrum of hopes and fears around the design, production and marketing approaches to the ZEMCH delivery in global contexts, ZEMCH Network was established in 2010. Today, the R&D collaboration network consists of over 630 partners from nearly 40 countries and the enrolment is constantly on the rise. Originally, the ZEMCH Network was formed by a group of academics, who participated in the 2010 industry-academia knowledge transfer technical visits to production and sales facilities of low to zero energy mass customised housing manufacturers in Japan. The technical tour, later called ZEMCH Mission to Japan, dates back to the 2006 operation and it celebrated the 10th anniversary in 2016.

The ZEMCH International Conference was initiated in 2012 and this year, the 5th congregation was celebrated in Kuala Lumpur, Malaysia. The ZEMCH 2016 International Conference encompassed the collective knowledge gained through global ZEMCH R&D activities. Firstly, I’d like to express my sincere gratitude to the ZEMCH 2016 Organising Committee Chair, Assoc. Prof. Ir. Dr. Mohd. Khairil Rahmat, for his leadership on the successful organisation and operation. Secondly, I am thankful to the Scientific Committee Chair, Dr. Arman Hashemi, for his rigorous peer-review process lead. At last, I’d also like to thank all the conference committee members, and ZEMCH Network’s global partners and regional experts centre directors for their generous, constructive support and cooperation. So far, ZEMCH Network established 5 regional centres in Brazil, Italy, UAE, UK and USA being responsible for the organisation and operation of annual industry-academia knowledge transfer events—i.e. ZEMCH Mission to Japan, ZEMCH International Conference, and ZEMCH Design Workshop. The success is rooted in the network partners’ individual efforts and collaborative actions. ZEMCH R&D activities have been thriven for continuous improvement of the built environments in developed and developing countries, budding out the global movement for people and society.

Masa Noguchi
ZEMCH Network Coordinator
University of Melbourne
Australia
PREFACES

The 5th international conference on Zero Energy Mass Custom Home (ZEMCH 2016) was successfully delivered in December 2016 at “Universiti Kuala Lumpur” in Malaysia. In its 5th year, the ZEMCH conference was greatly influenced by the challenging and ambitious targets of the Paris Agreement. Indeed, improving the energy performance of buildings, as a major source of greenhouse gas emissions, would significantly contribute to achieving the objectives of the agreement. The conference explored various subjects including the current and emerging design and construction methods, passive design, low/zero energy buildings, sustainable planning and management strategies, renewable energy and technologies, prefabrication, mass customisation etc. in both developed and developing countries in order to improve current practices and performances of the construction industry contributing to efforts towards mitigating the negative effects of climate change.

The ZEMCH 2016 Conference and proceedings have been divided into two main themes of Energy and Sustainability which are also a reflection of two MDPI sponsor journals (“Energies” and “Sustainability”) in which selected developed papers will be published. The first special issue namely “Building Energy Performance Evaluation/Simulation” will be published in Energies and aims to highlight and address the energy related challenges within the construction industry. The second special issue, “Climate Change Mitigation and Adaptation”, in Sustainability journal, explores the current sustainability issues within the construction industry. The third session of the proceedings is dedicated to the papers and poster presentation by MGEEB students and academics at UniKL.

I would like to thank the organising and scientific committees for their support and contributions. I would also like to thank all authors, delegates and individuals without whom this work would not have been possible.

Arman Hashemi
Editor & ZEMCH 2016 Scientific Chair
University of Brighton
United Kingdom
Warm greetings and welcome to all our ZEMCH-2016 participants who came all the way from different locations over the globe. Welcome to our committee teams, researchers, lecturers, staff and MGEEB-students.

The ZEMCH 2016 conference is the 5th important annual international gathering of green global architects and developers for Zero Energy Mass Customised Housing. With their academic research background, this community as a world wide operating network tries to present research-based new viable systems as contribution to curb global warming by green and energy efficient building technology.

Its recent back story relates to the December 2015 Paris Agreement with the ambitious Climate Agreement goals inhibiting the increment of global warming to maximum 1 degree C by 2050. As the overarching theme of this year’s conference based on the Paris Agreement, the buzzwords “implementation” and “action” are the ones that should echo into the future.

This is where ZEMCH 2016 may contribute via your presentations and discussions of its participants pertinent work. The series of all so far four annual ZEMCH conferences has a long-standing track record of innovation for Zero Energy Mass Housing, and it has the chance to channel scientific progress towards the goal of building inclusive and thriving low-carbon housing approaches. In order to achieve the ambitious Climate Agreement goals of the present and the future, ZEMCH also encompasses discussions that sustainability becomes an integral part of every country’s strategy, decision-making and disclosures. Science - just as government and developers – contribute and can be held accountable for the commitments given in Paris.

Thinking the triple bottom line of the UN further, it means green in terms of environment protection, indoor health and comfort and affordability. A promising project at UniKL called “Triple Green Mock-Up Building Park” will be target of our technical tour on Friday, where we are going to visit real-life test cells that try to help to set role models for ZEMCH housing of the future. I myself was one of the first supporters when I was still campus leader. That was the time when Prof Wagner addressed me about the project, which was seconded to me by the former President of UniKL, Prof Dato’ Abdul Hakim Juri. Even in my position as the Deputy President Academic Affairs of the University, I am still involved and keen to see things happen.

The story of Green Buildings at UniKL for our university begins 2009 in Germany when Prof Wagner was asked to import a program called MGEEB to Malaysia in a partnership with UniKL. The DAAD spent 430,000 EUR to build up the program and bring in the flying Faculty from Germany. But there was no product such as GEEB. What we had was just the idea of exporting profound German knowledge based on technology of the European Passive House from Prof Wagner’s home university UAS Rosenheim which is a proven global champion in green building technology.

Without further due, it is a time to say a big thank you to the UniKL team and everyone involved in the activities around the organisation. It is also time to say thank you to Dr Arman as the scientific chair of this conference acting from Brighton / UK, Dr Hasim from a university in Dubai for hosting the website and all others. Finally, thanks to you all for coming, sacrificing your time right before Xmas, may some of you also have happy
holidays in this part of the world during the festive season. Special thanks to our GEEB-students who are here to make and present their green research to make innovation for ZEMCH happen. Their poster and paper presentations will develop green information material out of the research at our mock-up houses that has been conducted since February 2015. I hope they can give their full support for Malaysia’s green future, hopefully encompassing their own professional future to play their part in assisting to reduce global warming after the implementation codes had been developed and signed by 180 over countries in Paris. Let us be there to make a difference!

So a cordial welcome one more time again to our conference, and .I wish you good progress, insights and success for ZEMCH globally.

Azanam Shah Hashim
Deputy President UniKL
Universiti Kuala Lumpur
Malaysia
MESSAGE FROM LOCAL ORGANIZING CHAIR

On behalf of the Local Organizing Committee, it is with great pleasure to announce that Universiti Kuala Lumpur has successfully worked in close collaboration with ZEMCH Network. The cooperation formed with ZEMCH Network is an achievement of what we strive at Universiti Kuala Lumpur in which we encourage strategic partnership with global industrial and technology partners. By doing this, we believe that we can continuously leverage all the latest technology and its resources for academic, research, humanity and mankind.

With no doubt, we have been expanding widely and continuously to contribute to the betterment of different aspects of daily life. Today, we are enjoying the discoveries of people who worked hard for the enhancement of life conditions. ZEMCH 2016 has been established as an excellent medium & platform that welcomes recent breakthroughs and studies in the energy & sustainability field to be made known and shared with not only everyone attending this conference but also the world.

We are certain that all us have benefited from the Conference and the gathering of great minds. Our utmost appreciation goes to the Conference delegates for their active participation and support. To the ever-hardworking Local Organizing Committee, your effort in making this conference a reality deserves a big pat on the back. Thanks to all sponsors and individuals who have supported and gave their utmost effort to make ZEMCH 2016 a successful event. THANK YOU!

Mohd. Khairil Rahmat  
ZEMCH 2016 Local Organizing Chair  
Universiti Kuala Lumpur  
Malaysia
SESSION I - ENERGY
EFFECTS OF DESIGN AND OPERATING PARAMETERS ON GREEN ROOF THERMAL PERFORMANCE IN MELBOURNE

Andrea Pianella¹,², Lu Aye², Zhengdong Chen³ & Nicholas S. G. Williams¹

¹ Green Infrastructure Research Group, School of Ecosystem and Forest Sciences, Faculty of Science, The University of Melbourne, Australia. apianella@student.unimelb.edu.au
² Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Parkville 3010, Australia.
³ CSIRO Land and Water Flagship, CSIRO, Australia.

Abstract: The growing interest in extensive green roofs prompts more refined studies on green roof design and operation. To assist in the design, installation and operation of green roofs, the effects of design and operating parameters on green roof thermal performance need to be fully understood. The effects of two design parameters: substrate thickness (ST), conductivity of dry soil (CDS) and four operating parameters: leaf area index (LAI), leaf reflectivity (LR), stomatal resistance (SR), moisture content (MC) were investigated using the green roof model developed by Sailor in 2008. The sensitivity analysis revealed that among the operating parameters, LAI has the largest effects on thermal performance. On the other hand, between the two design parameters CDS is more influential than ST. An experimental investigation in Melbourne of non-vegetated green roofs with three substrate thicknesses (10 cm, 15 cm and 20 cm) and on a bare conventional roof was employed to isolate the effect of plants and enable better understanding of heat transfer mechanisms involved. In contrast with the sensitivity analysis, the experimental results for summer and winter showed the importance of the ST in reducing the substrate temperature and heat flux across the green roof. They also showed how the green roof substrate alone reduces the heat flux compared to the conventional roof. Finally, the thermal performance of sparsely vegetated green roofs in summer revealed a contribution to cooling effect of plants.

Keywords: Green Roofs, Substrate, Thermal Performance, Heat Flux; Sensitivity Analysis.
1 Introduction
As part of efforts to reduce air pollutants and their carbon footprint (UNEP 2010; Castán Broto & Bulkeley 2013), cities and towns are introducing new technologies and techniques to mitigate some of negative impact of cities on the environment and make cities greener and more sustainable (Doulos et al., 2004, Omer, 2008, Sadineni et al., 2011). Green infrastructure is a potential solution (Chwieduk 2003; John et al. 2005). Green infrastructures are natural and engineered ecological systems integrated with the built environment to provide a wide range of ecosystem services, such as protection of urban biodiversity, air quality improvement, social and recreational opportunities, mitigation of stormwater runoff and urban heat island effect (Gill et al. 2007). Examples include permeable paving and bio-retention systems (rain gardens), urban forests, green roofs, green walls and green façades. Green infrastructures can also be integrated with buildings (green-gray infrastructures) to make them more sustainable and energy efficient (Tiwary & Kumar 2014). Among them, green roofs – also called vegetated or living roofs, are growing in popularity worldwide. Green roofs offer additional benefits such as decreasing building cooling and thermal loads, reducing building energy consumption and, to some extent, mitigating the urban heat island (UHI) effect (Berardi et al. 2014; Oberndorfer et al. 2007).

Studies have been conducted all around the world to quantify the extent to which green roofs reduce the heating and cooling loads of commercial and residential buildings. Findings are diverse and sometimes in contrast to one another. Common findings are that green roof thermal performance depends on the climate zone, the building materials and the green roof material selection (La Roche & Berardi 2014; La Roche et al. 2012). For example, in cold climate areas, a thick substrate enhances thermal performance compared to a thin substrate (Liu 2003). In contrast, in hot and wet climate areas, a thin 10 cm of substrate is sufficient to reduce the energy required for building cooling (Jim and Tsang 2011), while the greatest benefit to green roof thermal performance is offered by a dense and healthy vegetation (Jim 2012). For hot and dry climates, appropriate plant selection is essential because they need to be drought tolerant (Schweitzer and Erell 2014).

Because of these wide ranging results, it is not possible to specify an ‘optimum’ green roof build-up (plants and substrate or growing medium) that will maximise green roof thermal benefits in any country or climate zone. In situ research is therefore necessary to help select green roof materials in different areas (Pianella et al. 2016a).

Sensitivity analyses using existing green roof thermal models can help understand which parameters are most effective in enhancing green roof thermal benefits, and thus maximise green roof thermal performance in different locations. However, this is not sufficient, unless the results of the sensitivity analysis are validated with field measurements and a comprehensive thermal evaluation.

We investigated the effect of two design parameters and four operating parameters using the green roof model developed by Sailor (Sailor 2008). Results of the sensitivity analysis are presented in this paper. To verify the magnitude of the simulation outputs, we have also presented soil temperatures and heat fluxes of three non-vegetated and scarcely vegetated green roofs and the heat flux values of a bare conventional roof.
2 Materials and methods

Among the green roof thermal models developed and available from the literature, we have selected the green roof thermal model developed by Sailor (2008). The model is a phenomenological model based on Fast All-Season Soil Strength (FASST) model developed by Frankenstein and Koenig and it is available within EnergyPlus building energy simulation software tool (Frankestein and Koenig 2004).

Sailor’s model comprise many variables and parameters, some relevant to the vegetation layer, and others to the substrate layer, called soil in the model. We have selected three parameters for the vegetation layer and three parameters for the soil layer. These are: i) Leaf Area Index (LAI); ii) Leaf reflectivity (LR); and iii) Minimum stomatal resistance (SR); and, iv) Substrate thickness (ST); v) Conductivity of dry soil (CDS); and vi) Saturation volumetric moisture content (MC). These parameters were specifically selected to investigate the effects of design (ST and CDS) and operating parameters (LAI, LR, SR and MC) on green roof thermal performance.

Simulations were conducted with EnergyPlus 8.3.0. for a period of 30 days in summer (December 2014). Each input parameter was varied for three to four different values (Table 1). The EnergyPlus weather file for the simulations was prepared with the data collected by a weather station on top of the Main Building at The University of Melbourne’s Burnley campus. Data include ambient air temperature, ambient air relative humidity, rainfall, wind speed, wind direction and photosynthetically active radiation (PAR) collected every six minutes and averaged for one hour. Direct solar radiation was collected from another weather station located 500 m away from the roof weather station. Finally, infrared downward radiation was calculated using the model developed by Bras (Bras 1990).

To verify the results of the sensitivity analysis, we collected temperatures and heat fluxes of three experimental green roofs, and a bare conventional roof (no plants or substrates) on the Main Building at The University of Melbourne’s Burnley Campus (6 km from the centre of Melbourne).

Each of the three green roofs has an approximate area of 15 m². They have a scoria mix (volcanic rock) substrate layer either 100, 150 or 200 mm deep. Underneath the substrate layer, each green roof has a 0.6 mm filter layer (ZinCo filter sheet SF), a 40 mm drainage layer (ZinCo Floradrain® FD 40-E), a 5 mm protection layer (ZinCo SSM45 protection

<table>
<thead>
<tr>
<th>Input variable/parameter</th>
<th>Units</th>
<th>Input values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of plants</td>
<td>m</td>
<td>0.20</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>-</td>
<td>0.01 – 1 – 3 – 5</td>
</tr>
<tr>
<td>Leaf reflectivity</td>
<td>-</td>
<td>0.10 – 0.22 – 0.30 – 0.50</td>
</tr>
<tr>
<td>Leaf emissivity</td>
<td>-</td>
<td>0.95</td>
</tr>
<tr>
<td>Minimum stomatal resistance</td>
<td>s m⁻¹</td>
<td>50 – 150 – 180 – 30</td>
</tr>
<tr>
<td>Roughness</td>
<td>-</td>
<td>MediumRough</td>
</tr>
<tr>
<td>Thickness</td>
<td>m</td>
<td>0.07 – 0.10 – 0.15 – 0.30</td>
</tr>
<tr>
<td>Conductivity of dry soil</td>
<td>W m⁻¹ K⁻¹</td>
<td>0.20 – 0.35 – 0.40 – 0.80</td>
</tr>
<tr>
<td>Density of dry soil</td>
<td>kg m⁻³</td>
<td>1100</td>
</tr>
<tr>
<td>Specific heat of dry soil</td>
<td>J kg⁻¹ K⁻¹</td>
<td>1200</td>
</tr>
<tr>
<td>Thermal absorbance</td>
<td>-</td>
<td>0.90</td>
</tr>
<tr>
<td>Solar absorbance</td>
<td>-</td>
<td>0.70</td>
</tr>
<tr>
<td>Visible absorbance</td>
<td>-</td>
<td>0.75</td>
</tr>
<tr>
<td>Saturation volumetric moisture content of the soil</td>
<td>-</td>
<td>0.20 – 0.30 – 0.40</td>
</tr>
<tr>
<td>Residual volumetric moisture content of the soil</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Initial volumetric moisture content of the soil</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>Moisture diffusion calculation method</td>
<td>-</td>
<td>Advanced</td>
</tr>
</tbody>
</table>
mat), and a 0.36 mm high-density polyethylene (HDPE) root barrier. The roof of the building includes a 190 mm concrete layer and 10 mm of plaster board.

We first collected soil temperatures and heat fluxes from the green roofs in summer 2014 and winter 2015 before they were planted (non-vegetated), and then we collected data from the same green roofs when they were sparsely vegetated in summer 2015. Temperature data were collected with thermistors (Emerson, model 501-1125) placed at the bottom of the three green roofs in different locations. Heat flux for each roof was measured with heat flux plate (Hukseflux, model HFP01-L10m) placed at the middle, and underneath all the green roof component layers. Data were recorded every six minutes by a Campbell Scientific data logger (CR1000-4M) and averaged over one hour.

After data collection period for the non-vegetated green roofs, we planted them with three Australian high-water use plant species, namely Stypandra glauca, Dianella admixta and Lomandra longifolia. These plants were previously selected due to their high transpiration rates, but also because they can tolerate long drought periods common in Melbourne (Farrell et al. 2013). Plant foliage coverage was calculated through aerial photo pixel counts using Adobe Photoshop CC 2015 program. Photos were taken by a GoPro Hero4 Camera 4 m above the central point of each green roof.

2.1 Sailor’s green roof thermal model

The energy fluxes Equations (1-6) in Sailor’s model (2008) were developed from FASST vegetation model by Frankenstein and Koenig (2004). The model highlights two main fluxes: one for the soil (substrate) layer and the other for the vegetation. Each main equation incorporates both the sensible and the latent heat fluxes. The sensible flux is the heat exchanged by a body because of a change in temperature. The latent flux is the heat exchanged due to evaporative process at constant-temperature.

Energy flux for the soil [W m$^{-2}$]

$$F_g = (1 - \sigma_f)\left[l_s^f (1 - \alpha_g) + \varepsilon_g l_{ir}^v - \varepsilon_g T_g^4 \right] - \frac{\sigma_f \varepsilon_g \sigma_f \varepsilon_f}{\varepsilon_1} \left(T_g^4 - T_f^4 \right) + H_g + L_g + K \frac{\delta T_g}{\delta z}$$  \hspace{1cm} (1)

Sensible heat flux at the foliage/soil interface [W m$^{-2}$]

$$H_g = \rho_{ag} C_{p,ag} C_{h} W_{af} (T_{ag} - T_g)$$ \hspace{1cm} (2)

Latent heat exchanges of the soil [W m$^{-2}$].

$$L_g = C_e^g l_g W_{af} \rho_{ag} (q_{af} - q_g)$$ \hspace{1cm} (3)

Energy flux for vegetation [W m$^{-2}$]

$$F_f = \sigma_f \left[l_s^f (1 - \alpha_f) + \varepsilon_f l_{ir} - \varepsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \varepsilon_f \sigma_f \varepsilon_f}{\varepsilon_1} \left(T_g^4 - T_f^4 \right) + H_f + L_f$$ \hspace{1cm} (4)

Sensible heat flux at the atmosphere/foliage interface [W m$^{-2}$]

$$H_f = 1.1 \cdot LAI \ \rho_{af} C_{p,af} C_{f} W_{af} \cdot (T_{af} - T_f)$$ \hspace{1cm} (5)

Latent heat exchanges of the foliage [W m$^{-2}$].

$$L_f = \rho_{af} C_{f} W_{af} r''(q_{af} - q_{f,sat})$$ \hspace{1cm} (6)
3 Results and discussion

Results from the sensitivity analysis were simulated for 30 days in December 2014, but here are presented for only 10 days (2nd to 11th December). This was done primarily to aid interpretation through less condensed graphs (Figure 1 to 12). We selected two outputs from the simulations in EnergyPlus: the substrate temperature [°C] and the heat flux through the substrate [W m⁻²] (soil, in the model). The heat flux is calculated adding the ‘green roof soil sensible heat transfer rate per unit area’ with the ‘green roof latent heat transfer rate per unit area’ outputs. We have selected these two outputs to compare the results with the measured data from the experimental green roofs. Of the days simulated, there is unrealistic result for the third day (hours 48-72). This anomaly cannot be explained.

- Substrate temperature (Figure 13) and heat flux (Figures 14 and 15) data were analysed from the three experimental green roofs during the same period (2nd to 11th December 2014) for validation. Figures also show rainfall, ambient air temperature and total incoming solar radiation.
- Substrate temperature (Figure 16) and heat flux (Figures 17 and 18) data were analysed for 10 winter days (1st to 10th June 2015) to provide additional data of non-vegetated green roofs and discuss the effect of operating and design parameters during winter. Figures also show rainfall, ambient air temperature and total incoming solar radiation.

3.1.1 - Heat flux (Figures 19 and 20) for 10 summer days (11th to 20th December 2015) when the roof was sparsely vegetated. During this time, substrate temperatures were not collected. Figures also show ambient air temperature and total incoming solar radiation.

Heat flux of the bare roof was also collected and presented in Figures 14-15 and 17-20.

3.2 Sensitivity analysis

Among the vegetation and operational parameters, the sensitivity analysis showed that significantly higher LAI values reduced both the substrate temperature (Figure 1) and the heat flux (Figure 2). Reduction of the temperature was apparent during daytime and particularly for sunny days. The highest Leaf Area Index value (LAI = 5) reduced the temperature by up to 25°C compared to the lowest value (LAI = 0.01) (i.e. hours 0-24, 168-192). On cloudy days (i.e. hours 24-48, 120-144), the magnitude of this parameter was considerably reduced. Even though LAI = 5 offered the greatest temperature reduction benefits, results for LAI = 3 were less than 5°C higher than LAI = 5 at maximum. Results were similar on cloudy days. For heat flux (Figure 2), LAI = 3 and LAI = 5 offered a comparable result, meaning that a less dense vegetation can provide the same effect as very dense vegetation. In contrast, the other two vegetation and operational parameters tested (SR and LR) did not show such a significant benefit in all the simulations conducted.

Simulations were done keeping LAI = 1 to better isolate the effect of Stomatal resistance (SR) (Figures 3 and 4) and Leaf reflectivity (LR) (Figures 5 and 6). On some dry days (i.e. hours 0-24, 216-240 Figure 13), simulations of high SR values showed a considerable difference compared to simulations of low SR values. For example, substrate temperature of SR = 300 simulation was up to 4°C higher than SR = 50 (hours 216-240). This is because high stomatal resistance value translates into a low transpiration rates, as the plants attempt to conserve water, and thus have a lesser cooling effect.

We have not found any soil parameter that significantly reduced soil temperature or the heat flux. However, this was expected because the simulations only consider the interface between vegetation and soil; hence, they overlooked the benefits of the layers underneath this interface (i.e. the whole substrate layer, the drainage layer, etc.).
Surprisingly, there was little effect of varying the design parameter substrate thickness (ST) (Figures 7 and 8) as simulation results were consistent for all values, except on two dry days (i.e. hours 72-96, 210-225) where the thickest extensive green roof substrate (ST = 0.30) had cooler temperatures than the other values. Heat flux of the thickest substrate on these days was lower (Figure 8), meaning that larger thermal mass, when dry, can provide a better cooling effect.

The Conductivity of dry soil (CDS) design parameter (Figures 9 and 10) showed varying results for most days across all simulations. CDS = 0.2 simulated temperatures up to 5°C higher than CDS = 0.8 on sunny days (i.e. hours 144-168, 168-192), while provided similar temperatures as the other simulations on cloudy days (i.e. hours 120-144, Figure 9). Similarly, for the heat fluxes (Figure 10), differences were more evident on sunny days, even though without a clear pattern. Although not clearly revealed in the sensitivity analysis we performed, the importance of the CDS for the green roof thermal performance was shown in a previous study (Pianella et al. 2016b).

Finally, the operation Moisture Content (MC) soil parameter showed small differences (~2°C) in the temperature peaks on sunny days (i.e. hours 168-192, Figure 11), or difference happened during the hours where a rainfall event occurred (i.e. hours 48 and 96). However, results were difficult to interpret for the soil temperature outputs, while they were generally uniform for the heat flux output (Figure 12).

The sensitivity analysis has provided limited insight into the effects of the parameters tested, with the exception of LAI operational parameter. To better understand their effect, field measurements are recommended, in particular for those parameters with unrealistic results, such as ST and MC. The next section provides results from experimental roofs in Melbourne.

### 3.3 Thermal performance of non-vegetated green roofs in Melbourne in summer and winter

Temperatures and heat fluxes were collected from three non-irrigated and non-vegetated green roofs and one bare conventional roof (heat flux only) in Melbourne for the same duration selected for the sensitivity analysis (2nd to 11th December 2014). Figure 13 showed the temperature at the bottom of three non-vegetated green roofs with thickness of 100, 150 and 200 mm. Temperature fluctuations were wider on sunny dry days (i.e. hours 0-24, 168-192) than cloudy rainy days (i.e. hours 24-48, 120-144) for every green roof and, as expected, the 100 mm green roof had the largest fluctuations on all days. The temperature difference between the 150 mm green roof and the 100 mm green roof was greater than between the 200 mm and 150 mm green roof, particularly on cloudy days. This suggested that the insulative effect of the additional thermal mass may increase until a green roof thickness of 150 mm and then may approach asymptote when the substrate is thicker than 150 mm.

Generally, the daily temperature peak was delayed in every green roof, and the thickest green roof had the lowest temperature peak, which was delayed up to four hours later than the thinnest green roof in this study. Peak reduction and delay was also confirmed from the results of the heat flux measurements (Figures 14 and 15), where the 200 mm green roof delayed the heat flux peak up to eight hours compared to the heat flux of the bare roof (not shielded). As the heat flux measurements were collected at the interface between the building roof and the green roof, they took into account the effect of all the green roof component layers, and not only the substrate. Under this condition, the heat fluxes for the
150 mm and 200 mm green roofs were comparable, proving that a 150 mm thick green roof may provide the same insulation effect of a thicker green roof. On cloudy and rainy days, however, the differences among the three green roofs were minimal.

The thermal benefits from different substrate thicknesses were not reported on the sensitivity analysis of the ST design parameter, where the soil temperature and heat flux were simulated by default at the interface between the substrate (called soil) and the vegetation, rather than below all the green roof component layers.

Winter data (Figures 16-18) partially confirmed the main findings of the summer period, although with smaller temperature and heat flux differences among the three non-vegetated roofs. Rainy days did not smooth the temperatures, but instead increased the temperature variations: the 100 mm green roof recorded the lowest temperature, while the 200 mm the highest (Figure 16). The heat flux values had comparable results for the 150 mm and 200 mm green roofs, although the heat flux for the 200 mm green roof was always negative on the tested days, and the one contributing the most at the peaks delay and reduction (Figures 17 and 18).

In summary, we found that the thicker substrates provided large benefits for the thermal performance of green roofs reducing and delaying the heat flux into the building, however this delay effect was not observed in the sensitivity analysis. The operational parameter MC influenced the substrate temperatures more in winter than in summer.

3.4 Thermal performance of sparsely vegetated green roofs in Melbourne in summer

The green roofs were planted in October 2015, and the vegetation coverage in December 2015 was around 20%. Heat flux data were collected from 11th to 20th December 2015. Unfortunately, during summer 2015, temperatures for the green roof substrates were not collected. This period had mostly dry days, except for a few showers on the first (cumulative rain of 1.6 mm in a period of eight hours) and last day (cumulative rain of 4.4 mm in a period of 12 hours), therefore the green roofs were irrigated to maintain plants health and growth. There was a heat wave event with temperatures between 35°C and 41.5°C for four consecutive days from 17th to 20th December. Although vegetation cover was sparse, the plants helped mitigated the impact of the incoming solar radiation, particularly for the 200 mm green roof. The heat flux of the 200 mm green roof (Figure 19 and 20) showed a distinct and smaller fluctuation than the 150 mm green roof. In contrast, when non-vegetated, the heat flux of the 150 and 200 mm green roofs mostly coincided. This is likely due to the large amount of water present in the thicker green roof and, consequently, to the highest amount of water transpired by the plants and evaporated from the substrate. Likely, the cooling effect of plants will be enhanced for denser green roofs. Nonetheless, the heat flux difference between the 150 and 200 mm sparsely vegetated green roofs is minimal, suggesting, again, that the thermal performances of the 150 and 200 mm green roofs are comparable when including all the green roof component layers.

The total dead load of a 200 mm thick vegetated green roof is ~2.5 kN m$^{-2}$ when using scoria as main substrate component, while it would increase up to ~3.15 kN m$^{-2}$ when using crushed roof tile or any other heavy material as substrate main aggregate (Pianella et al., 2016b).

Under this circumstance, a 50 mm thinner substrate made of scoria would have less weight [between 0.466 (dry) and 0.554 (saturated) kN m$^{-2}$] and would be a more viable option to retrofit to a wider range of existing building. In fact, while the extra dead load would be
negligible for commercial buildings (Sofi et al. 2014), this might not be the case for most of Melbourne low-rise residential buildings.

4 Conclusions

Extensive green roofs are being used to reduce the environmental impact of buildings on cities and surrounding areas. Their growing popularity prompts more refined studies to improve their design, installation and operation, and understand the effect of design and operating parameters.

A sensitivity analysis using Sailor’s (2008) green roof thermal model was undertaken using Melbourne conditions and found that that LAI (for the vegetation layer) and CDS (for the substrate layer) had the most influential effects on the green roof thermal performance. In particular for LAI, the sensitivity analysis suggests that LAI = 3 provides comparable outcomes to a denser vegetation, such as LAI = 5.

Thermal measurements from three green roofs (non-vegetated and sparsely vegetated) with three different substrate thicknesses and a bare conventional roof were collected to quantify evidence of the effect of design and operational parameters.

The measured data from the experimental roofs showed that:

a) The green roof substrate alone significantly reduces the heat flux at the building-roof interface compared to a bare conventional roof and delays heat flux into the building up to eight hours;

b) Substrate thickness (ST) has large positive effects on green roof thermal performance. This benefit is not revealed by the sensitivity analysis because the green roof soil outcomes refer to the interface between substrate and vegetation, rather than to the interface between the building original roof and the green roof;

c) The thermal performance of green roofs with 150 and 200 mm thick substrates are generally comparable when considering the effects of all the green roof component layers. Consequently, the 150 mm thick green roof would be a more widely applicable option for building retrofit due to its lighter weight than the 200 mm green roof (0.466-0.554 kN m$^{-2}$);

d) As research has shown that the thermal performance of green roofs varies significantly across different climate zones and buildings, results from green roof simulations should be validated with experimental green roofs. This will help design and select green roof materials in different areas.

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Nomenclature

$C_{eg}$ bulk transfer coefficient for latent heat near the ground
$C_{f}$ bulk transfer coefficient for turbulent heat in the foliage
$C_{hg}$ bulk transfer coefficient for sensible heat near the ground
$C_{p,a}$ specific heat of air
$E_a$ atmospheric emissivity
$e$ vapour pressure
$e_s(T_a)$ saturated vapour pressure at the air temperature
$H_f$ sensible heat flux at the atmosphere/foliage interface [J m$^{-2}$]
$H_g$ sensible heat flux at the foliage/ground interface [J m$^{-2}$]
$I_{s,i}$ total incoming infrared radiation [W m$^{-2}$]
$I_{S,i}$ total incoming solar radiation [W m$^{-2}$]
$K$ von Karmen constant
$LAI$ Leaf area index [m$^2$ m$^{-2}$]
$L_f$ latent heat exchanges of the foliage [J m$^{-2}$]
$L_f$ latent heat of vaporization at the foliage temperature [J kg$^{-1}$]
$L_g$ latent heat exchanges of the ground [J m$^{-2}$]
$L_g$ latent heat of vaporization at the ground temperature [J kg$^{-1}$]
$q_{af}$ mixing ratio of the air at the foliage interface
$q_{s, sat}$ saturated foliage mixing ratio
$q_g$ mixing ratio of the air at the ground surface
$r^*$ surface wetness factor
$r_a$ aerodynamic resistance to transpiration [s m$^{-1}$]
$r_s$ foliage leaf stomatal resistance [s m$^{-1}$]
$T_a$ air temperature [K]
$T_{af}$ air temperature in the foliage [K]
$T_f$ temperature of foliage [K]
$T_g$ temperature of the ground surface [K]
$W_{af}$ wind speed in the foliage [m s$^{-1}$]
$z$ depth of the substrate [m]
$\alpha_f$ shortwave albedo for the foliage [0 – 1]
$\alpha_g$ shortwave albedo for the ground surface [0 – 1]
$\varepsilon_f$ $\varepsilon_f + \varepsilon_g - \varepsilon_f \varepsilon_g$
$\varepsilon_f$ longwave emissivity of the foliage [0 – 1]
$\varepsilon_g$ longwave emissivity of the ground surface [0 – 1]
$\rho_{af}$ density of air near the atmosphere/foliage interface [kg m$^{-3}$]
$\rho_{ag}$ density of air at the ground temperature [kg m$^{-3}$]
$\sigma$ Stefan-Boltzman constant

References


EVALUATING THE THERMAL PERFORMANCE OF LOW-INCOME HOUSING IN THAILAND

Nafisa Bhikhoo¹, Arman Hashemi² & Heather Cruickshank³

¹ Department of Engineering, University of Cambridge, UK, nafisabhikhoo@gmail.com
² School of Environment and Technology, University of Brighton, UK, a.hashemi@brighton.ac.uk
³ Smart Villages, Cambridge, UK, heather@es4v.org

Abstract: This research investigates potential areas for improving the thermal performance of low income, government-provided housing designs in Bangkok, Thailand. In a country that experiences hot and humid temperatures throughout the year, buildings need to be adaptable to the climate in order to improve the thermal comfort of inhabitants. The current housing typologies include a prevalence of high density, low-rise condominiums with a large brick and concrete composition. As an initial step, the performance of the building was determined according to adaptive comfort standards using IES (VE) software. The results from the baseline model were analysed according to the adaptive comfort CIBSE TM52 guidelines. The zones under consideration within the case study housing unit were observed to exceed the acceptable limits of what is deemed appropriate for naturally ventilated buildings. The critical zone of concern is the living room with this zone exceeding the upper limit for overheating by a maximum of 11 hours annually. The main sources of the low thermal performance were identified as resulting from: thermal storage effects, the lack of sufficient natural ventilation through the living zones and excessive heat gains through the roof. The internal operating temperatures of the apartment remain high throughout the day and night, ranging from a maximum of 38.5°C to a minimum of 27.3°C.

Keywords: Thermal Comfort, Low Income Housing, Thailand, Tropical Climates, Dynamic Thermal Simulations
1 Introduction

The consequences of rapid population growth and urbanization in the context of the limited availability of resources have exposed the immediate need to address underlying social circumstances which are attributed to the prosperity of both individuals and the natural world (Golubchikov & Badyina 2012; Hannula 2012). In the developing world the inadequacies of the current housing systems have been exposed. The accessibility of affordable housing is limited by the socio-economic status of those who need it (French et al. 2011) and the quality of the current stock of low income housing is characterised by technical inefficiencies and inappropriate design elements thus rendering it inadequate for day to day living. With concerns growing over urban liveability in these regions, priorities need to be placed on planned future development (Hannula 2012). This involves a shift towards the provision of housing that not only make use of environmentally sensitive construction materials, processes and technologies, but also considers how housing performs under the effects of both internal and external climatic factors (Golubchikov & Badyina 2012). This results in housing that promotes equity and social inclusion amongst communities and the poorest residents. Essentially advances need to be made in the supply of dwellings that reduce the vulnerabilities of inhabitants to future hazards and contribute to resilience, while remaining affordable (French et al. 2011).

In urban areas of Thailand, the adoption of western housing design standards and inadequate standards for thermal comfort assessment in tropical regions (Nicol 2004) means that affordable housing projects are planned and designed without climatic considerations. The inadequate adaptation of these buildings to the prevailing climate results in extreme indoor temperatures and reduced comfort. The Baan Ua-Arthorn programme is an example of a top-down governmental approach to providing housing for the lower income bracket of the population in Thailand (Kritayanavaj 2012; Usavagovitwong et al. 2013). The low cost housing development programme was implemented in 2003 as a means to enhance economic growth in the country, with the intention of constructing 600 000 homes (Kritayanavaj 2012) within a five year period. During an eight year period of implementation the National Housing Authority completed just over 250 000 housing units. These units range in design from low-rise condominiums and single detached houses to semi-detached houses and townhouses. The breakdown of housing unit types shows that during the period of the project implementation over 180 000 of the 253 164 houses constructed included low-rise condominiums. The average construction cost of one of these low income condominiums equates to 8000 THB per m² (Suenderman 2015). Due to the low cost nature of these housing estates, the units are characterised by their use of inadequate materials (Chiarakorn et al. 2014), the inferior quality of the design and the construction, and located in hard to reach urban zones (Archer 2010).

The climatic conditions in Thailand are characterized by three distinct climatic periods. The hottest temperatures are experienced from March to May, the rainy season occurs from June to October and a relatively colder period occurs from November to February (Antarikananda et al. 2006). The mean daily temperature ranges from 26°C-36°C C with the average minimum temperature falling to 21°C in the ‘winter’ months with the annual average temperature reaching 28°C (Bangkok Climate & Temperature 2015). The relative humidity remains high throughout the year averaging 74%-85% and peaking during the rainy months. Daytime temperatures are found to exceed those temperatures deemed thermally comfortable throughout the year (Suenderman 2015).
The incorporation of architectural specifications in the government-provided low income housing (which are incompatible with the prevailing climatic conditions of Thailand) is found to exacerbate issues associated with extreme indoor temperatures and comfort, adequate natural ventilation and low levels of indoor air quality in these dwellings (Santamouris et al. 2007). This has induced a dependency on mechanical forms of cooling once individuals can afford it (Antarikananda et al. 2006) and the residential energy consumption in Thailand set to increase more than twofold by 2030 (Suenderman 2015). The construction of housing that can adapt to dominant climatic conditions is a key element of providing appropriately sustainable housing and reducing energy consumption in an urban context (Hannula 2012).

The use of passive design strategies is proposed as an adequate method to achieve optimum indoor environmental conditions in residential buildings and thus reduce energy consumption (Antarikananda et al. 2006; Santamouris et al. 2007; Suenderman 2015). The distinct nature of the tropical climate means that housing design needs to incorporate strategies that exploit the benefits from the outdoor climate to achieve thermal comfort inside (Jayasinghe et al. 2002). The main design consideration is incorporating elements that minimise internal heat gains and maintain thermal comfort of inhabitants during periods of high solar radiation and relative humidity. The construction of housing that can adapt to these dominant climatic conditions is a key element of providing appropriately sustainable housing and reducing energy consumption in an urban context (Hannula 2012).

To this end, this paper intends to quantify the thermal performance of a single condominium housing unit under the Baan Ua-Arthorn programme. Under the long term outcomes of the ELITH project, this study aims to analyse elements of the building envelope that influence building performance and thereby make recommendations on viable options to solve the inadequacies. This study does not to propose a redesign or new concept design of low income housing for the National Housing Authority, but to indentify the dominant passive cooling strategies and areas of concerns that should be incorporated into low income housing design in this region.

2 Research Methodology

A case study housing design is established be used as a baseline example for assessment. Dynamic thermal simulations are conducted in IES VE to evaluate the thermal performance of low income housing in terms of material composition and design strategies under specific macro climate conditions.

The case study building including the prevailing roofing system (i.e. 5mm slate tiles) is simulated in combination with the standard walling materials (i.e. brick and cement rendering) for a fixed wall thickness of 200mm. A single combination scenario is run incorporating the material characteristics shown in Table 1. The baseline results are then validated according to adaptive thermal comfort standards to assess whether the internal temperatures exceed the acceptable thermal comfort threshold throughout the year and the margin by which these conditions are exceeded.
Table 1: Material description of typical housing unit (CIBSE 2007)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Thickness (m)</th>
<th>Surface Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof tiles</td>
<td>6.266</td>
<td>5mm</td>
<td>0.51</td>
</tr>
<tr>
<td>External Walls Clay brick and cement rendering</td>
<td>2.246</td>
<td>200 mm</td>
<td>0.75</td>
</tr>
<tr>
<td>Internal Partitions Concrete Block</td>
<td>3.384</td>
<td>100 mm</td>
<td>0.90</td>
</tr>
<tr>
<td>Windows glazing</td>
<td>2.7465</td>
<td>6 mm</td>
<td>0.90</td>
</tr>
<tr>
<td>Ceiling Gypsum</td>
<td>1.255</td>
<td>90 mm</td>
<td>0.85</td>
</tr>
<tr>
<td>Floor Reinforced concrete</td>
<td>3.618</td>
<td>250 mm</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The floor plans of the original housing designs were provided by the NHA. Each of the apartments is composed of five rooms, namely: a balcony, a toilet, a living room, a bedroom and a kitchen. The bedroom is the only room with an outside facing window, while the kitchen and the living room both contain windows overlooking the internal hallway. The balcony is accessed through a door from the living room. The windows are set at dimensions of 1.5 m x 1.5 m and are situated 1 m above the base. The doors are set at 0.9 m x 2.5 m. Based on the concepts of zoning, each room in the apartment was identified as an individual zone for DTS purposes.

The typical occupancy pattern for the apartment includes an average of four people with working hours spanning from 8 am to 6 pm during the week. The apartment is considered as occupied during all other hours. The internal gain associated with sedentary person is 90 W/person/day and the gains associated with appliances include 106 W/m² from a gas cooking stove (Ministry of Information and Communication Technology 2013; The Chartered Institution of Building Services Engineers 2006). The buildings are free-running and include no forms of mechanical cooling (Suenderman 2015). The schedule of openings for the baseline model was created on the basis that windows are all open during the day and closed during the night. The house windows are all defined as louvre windows and the window openable area is 25%. The openable area for the doors was set to 50%. The balcony was modelled as a window that is continuously open at 100%.

For this study the weather data over a twelve month period for the Bangkok Metropolis (13.73° N, 100.57° E) is selected. The orientation for the baseline model is set to south facing. This is to simulate the worst case scenario for solar gains and to maximise the effect of the local shading devices over the bedroom windows.

Adaptive model Category II (normal expectation for new buildings and renovations), defined in BS EN 15251 (British Standards Institution (BSI) 2007) along with the following overheating criteria, defined in CIBSE TM52, are used to evaluate the risk of thermal discomfort (Table 2).

Table 2: Overheating assessment criteria

<table>
<thead>
<tr>
<th>Assessment Criteria*</th>
<th>Acceptable Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria 1</td>
<td>Percentage of occupied hours during which ΔT (ΔT ≤ Top - Tmax rounded to the nearest whole degree) is greater than or equal to 1°C</td>
</tr>
<tr>
<td>Criteria 2</td>
<td>“Daily weighted exceedance” (We) in any one day &gt;6 °C.h (degree hours)</td>
</tr>
<tr>
<td>Criteria 3</td>
<td>Maximum temperature level (Tupp) ΔT &gt; 4 °C</td>
</tr>
</tbody>
</table>

* Refer to Abbreviations for more information.
3 Results and Discussion of Simulations
The simulations section evaluates the thermal comfort conditions based on the standard material composition of Baan Ua-Arthorn housing.

3.1 Performance of Baseline Model of Case Study Housing Unit
The results of the thermal performance of the baseline model were validated according to adaptive thermal comfort standards.

3.1.1 Hours of Exceedance (He)
In Fig.1, the percentage of hours of exceedance is shown for the living zones on the ground floor and the fourth floor. The initial observation is that the apartments greatly exceed the limiting factor of 3%. The apartments on the fourth floor are shown to have worse thermal performance than those on the ground floor. The worst performing apartment is the edge unit on the top floor (with two exposed external walls). The living room in this unit is the worst performing zone with a performance that exceeds the limiting factor by over five times at a value of 16.14%. The bedroom exceeds the limiting factor by over three times with a value of 10.06%.

![Figure 1: Performance of apartment according to criteria 1](image)

3.1.2 Daily Weighted Exceedance (We)
This criterion was assessed by counting the number of days in a calendar year where the We exceeds 6°C/hr while that zone was occupied. In compliance with criteria 2, a zone should exceed this value for no days. The results for the baseline case are shown in Fig.2. As with criteria 1, the apartments are shown to exceed the limits of failure with the corresponding top floor apartment showing the greatest signs of overheating. Within this apartment the living room surpasses 6°C/ hr for 115 days and the bedroom surpasses 6°C/ hr for 77 days out of 365 days respectively. This indicates that the zones within the apartment spend a large percentage of time at very high temperatures throughout the year.
3.1.3 Upper Temperature Limit for Overheating

The apartments on the lower ground are again found to perform better than those on the top floor. The living room is observed to be the critical zone within the apartments as it fails criteria 3 for three of the four apartments (Fig.3). The differentiation in the performance of the apartments on the lower floor is attributed to the location of the apartments. The unit with two exposed walls (apartment 1) has reduced capacity for providing thermal comfort within the adaptive comfort limits. The living room in apartment 1 on the ground floor and top floor exceed 4°C by 4 hours and 11 hours annually, respectively.
The apartment with the poorer thermal performance was shown to be apartment 1 on the top and ground floors. This is attributed to the material properties of the structural features of the building envelope. This apartment is constructed with two exposed external walls allowing for a higher rate of heat transfer.

In conjunction with the location of the apartments on a level, the height of the condominium influences the thermal performance of the apartments. The building is subjected to effects from ‘buoyancy-driven air movement’ (Suenderman 2015). Hot air from the lower levels rises up through the building and with no means of escaping the living zones, accumulates on the top levels. Combining this with the effects from the building envelope corresponds to the inadequate thermal performance of apartment 1 on level four for all 3 criteria.

In terms of criteria 3, the bedrooms in each of the apartments do not show exceedance of 4°C over the year. This can be attributed to the classification of the bedroom as a ‘night-zone’ (Garde et al. 1999) which means it is only occupied at night. These criteria are assessed based on when the zone is occupied. This means that the external night time temperature drop below a certain point whereby the addition of internal gains from people is not significant enough to raise the temperature above Tupp. In comparison, the living room is either partially or fully occupied at all times. This incorporates those periods where external daytime temperatures reach their maximum.

While these results show that this housing model far exceeds what is deemed acceptable for TM52 it is important to note that TM52 is designed as a tool for mainly assessing overheating in summer in Europe and the UK. Thus its application to tropical climates tends to underestimate the amount of time spent at high temperatures (which in these regions is most of the day). This is particularly significant for the application of criteria 2. While this level of severity of overheating may be more unacceptable in temperate zones, inhabitants in Thailand are less critical of these conditions. These observations also correlate with those made by Eyre (2015) for low income housing in Tanzania and should be incorporated into continued research into establishing adequate thermal comfort criterion for tropical regions (Nguyen et al. 2012).

### 3.2 Summary of Findings

#### 3.2.1 Diurnal Temperature Fluctuation

The 24-hour temperature profiles of the living room, the bedroom and the kitchen for the hottest day of the year (29 April) are shown in Fig.4, Fig.5 and Fig.6 respectively. The variation of room temperature with time shows a low diurnal temperature swing with the internal temperature patterns correlating to the external temperature changes. The internal operating temperatures remain relatively high throughout the day and night, fluctuating between the maximum acceptable temperature and the upper limit for overheating. The external night temperatures do not drop significantly enough to induce rapid cooling of the indoor environment.
Figure 4: Diurnal temperature variation of living room

Figure 5: Diurnal temperature variation of bedroom

Figure 6: Diurnal temperature variation of kitchen
3.2.1.1 Influence of Building Envelope on Thermal Performance

The thermal mass has a significant influence on the cyclical nature of the temperature changes within the apartment units. As the external air temperature rises, the external walls and floor slab will absorb and store the heat. Once the external temperatures start to drop (7 pm) the heat within these materials rises to the surface and is released into the internal environment. This elevates the internal night temperatures of the living zones. This process is represented in Fig. 7, where the fluctuations in the conduction gains of the external walls are influenced by changes in the outdoor temperature. This has the resultant effect of moderating the operating temperatures of the living zones. The critical issue is that this effect keeps the operating temperatures at high levels throughout the day, inhibiting sufficient cooling to occur.

![Figure 7: Thermal storage effect of external walls](image)

In this study the windows were assumed to be closed at night due to security and social reasons. This limits the amount of airflow in the apartment at night, particularly in the bedroom which has only one window. With insufficient mechanisms to abate excess heat that is released into the zone at night, the operating temperatures of the apartment remain elevated. Fig. 8 shows that about a 2°C reduction in the operating temperature is induced in the bedroom if the window remains open at night and airflow is improved.

![Figure 8: Improvement of ventilation with night cooling](image)
3.2.1.2 Influence of Natural ventilation on Thermal Performance

The high internal operating temperatures are a result of both convection and radiation heat which build up over the day. Without any form of mechanical cooling natural air exchanges are responsible for the removal of this heat; however the current construction of the building and each apartment has a significant influence on the ventilation. While the narrow layout may aid in the circulation of air, the number and type of openings, the layout of the rooms and the restrictions of adjacent apartments means that ventilation between rooms is highly restricted. Fig.9 shows the quantity of airflow that enters into each zone. The value \( W_c \) refers to the minimum wind speed that is needed to ensure indoor comfort is maintained (Tantasavasdi et al. 2001). The daytime flow rate ranges from 0.11 m/s to 0.38 m/s. The windows remain closed at night which accounts for this rate dropping to zero overnight. The maximum airflow rate in the living room and kitchen is 0.81 m/s and 2 m/s respectively. To achieve a comfortable indoor environment, natural ventilation should provide an indoor air velocity of 0.4 m/s.

![Figure 9: Rate of airflow through the apartment on 29 April 2010](image)

Essentially the amount of cross ventilation that can occur through a single unit is highly restricted by design elements and local climatic conditions. The heat builds up and with no method of removal stagnates to increase the operating temperature as well as the discomfort of the internal environment.

3.2.1.3 Influence of Roof on Thermal Performance

The analysis of the progression of the operating temperature change over the 24 hours showed that the roof is subject to a significant temperature change over the course of the day. The temperature change in the roof is seen to begin at 09:00 as the external temperature rises and the solar radiation increases (Fig.10). The temperature of the apartments is seen to be about 5°C higher than in those on the ground floor at this time. By 14:00 the roof reaches its highest temperature.
The corresponding conduction gains in the roof over 24 hours are shown in Fig. 11. The conduction values range from a minimum of 1.98kW at 07:00 to a maximum value of 21.86kW at 12:00. This corresponds to the increase in direct solar exposure over the day. The negative gains during the night are associated with reversal in the direction of heat transmission i.e. the roof temperature is higher than the external temperature.

Various DTS studies that have been carried out on houses in tropical regions have shown that the roof is a key area of concern in terms of thermal performance (Hashemi 2016; Eyre 2015; Garde et al. 1999; Jayasinghe et al. 2002). The roof is continually exposed to high levels of solar radiation and materials used in roof construction tend to have low thermal storage and low thermal resistance properties. This means that a building remains vulnerable to high levels of heat transmission occurring through the roof. In the case study building, there is a significant difference in operating temperatures between the apartments on the upper level and those on the ground floor. This is partly due to the stack effect of air; however this can also be attributed to the high magnitude and the rapid transmittance of heat energy through the roof.

4 Conclusion
This paper evaluated the thermal performance of the dominant housing designs under the Baan Ua-Arthorn housing programme Bangkok, Thailand. Dynamic thermal Simulations (DTS) of the case study housing units were conducted with IES VE in order to determine weaknesses in the design in terms of providing thermal comfort to inhabitants to be
The results were assessed according to the CIBSE TM 52 guideline for assessing overheating in naturally ventilated buildings. It was observed that the building failed to comply with the limits of overheating established by this guideline. The primary concerns include the severity of overheating far exceeds what is deemed appropriate for achieving a comfortable internal environment and the living zones breached the absolute daily maximum daily temperature limit. This means that the current housing designs are not adequate for establishing a comfortable living environment for the inhabitant in this climate.

The main sources of the low thermal performance quality in these apartments were identified as resulting from:

I. Thermal storage effects due to the high thermal mass of the apartment walls and floor.

II. The lack of sufficient natural ventilation through the living zones resulting from the high levels of humidity and low natural wind speeds in the area but exacerbated by a poor indoor layout and a lack of sufficient openings in the building envelope.

III. The high conduction gains through the roof resulting from its inadequate material properties.

This paper intended to assess the adequacy of Baan Ua-Arthorn material composition and design techniques to further research around low cost design strategies for more sustainable housing supply in tropical climates. A sensitivity analysis is required to identify the parameters that have the most effect on the thermal performance. These results will be used to make recommendations based on the adequacy of the design strategies in naturally ventilated buildings in consideration of the Thai context. Further research is also required to establish the effects of potential climate change, the quantitative comparison between using mechanical cooling with passive design features and the social constructs regarding the perception of modernity and mechanical cooling. The economics of incorporating passive design elements in low income housing projects in Thailand should also be considered.

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References


A FEASIBILITY ANALYSIS OF RETROFITTING LIGHTING SYSTEM FOR HAMDAN CENTRE IN ABU DHABI, UAE

Aia Sherif\textsuperscript{1}, Hagar Shalaby\textsuperscript{2} & Hasim Altan\textsuperscript{3}

\textsuperscript{1}Sustainable Design of the Built Environment, Faculty of Engineering & IT, the British University in Dubai, Dubai, UAE \texttt{aia.m.sherif@gmail.com}
\textsuperscript{2}Department of Architecture, Faculty of Engineering, Alexandria University, Alexandria, Egypt, \texttt{haidyyy@gmail.com}
\textsuperscript{3}Department of Architectural Engineering, College of Engineering, University of Sharjah, Sharjah, UAE, \texttt{haltan@sharjah.ac.ae}

Abstract: In a country that is considered as one of the leading countries in the region for oil production, energy efficiency is thought to be insignificant to some. However, the government in the UAE is fully aware of the problem of the rapid increase in its energy consumption and that it directly affects more use of non-renewable energy sources presented in fossil fuels. Reducing the current energy consumption is thought to be difficult to achieve, since it is directly related to people’s behavior and life style, still the UAE has set very strict regulations and strategies in order to achieve remarkable reductions in energy consumption. For new buildings or developments taking place in the capital, some regulations and guidelines should be applied in the design phase, and during construction and operation phases in order to make sure that the building is operating as designed. The Pearl Rating System is a mandatory rating system that was adopted originally from the US Green Building Council’s LEED certification while edited in a way to be more suitable for the gulf region. Nevertheless, it is mandatory for only new buildings and developments but what about the existing ones, especially those that are built few decades back when there was no consideration about global warming or energy consumption. Those buildings are considered as vast energy consumers as their systems are very old and in many cases, they are not properly maintained. Recently, this problem started to gain attention and the Emirates Green Building Council launched a new manual for existing buildings’ retrofitting in collaboration with the Ministry of Public Works and the Supreme Council of Energy, however, it is not mandatory yet. The study is presenting a case study building, which is one of the oldest buildings in Abu Dhabi, and is assessing its services for energy efficiency. The paper studied the building in detail by monitoring and documenting what the existing building services are, current conditions of those services, breakdown of energy consumption, maintenance procedures, and whether they need immediate repairing or even replacement. In conclusion, lighting system has been investigated in detail to come up with a list of recommendations that could help reduce its energy consumption.

Keywords: Lighting Systems, Retrofitting, Sustainable Development, Energy Consumption, Energy Efficiency.
1 Introduction

The UAE is witnessing a huge development in the field of energy conservation. Although it is considered as one of the leading countries in oil production, it is also one of the first countries in the region that took serious actions to reduce energy consumption and shift to renewable, clean energy sources. Energy conservation can be defined in two major categories; the first is finding a clean and renewable energy sources instead of fossil fuels sources. This solution is considered as a long term and costly solution that should be implemented and developed by governments. The second one is to reduce the current consumption of energy and this sounds to be a very difficult objective to be achieved. Considering the rising populations and the high standard of living that UAE residents are enjoying, reducing energy consumption sounds impossible. Yet the government has taken some serious actions to help solving the growing problem. HH Mohamed Bin Rashid Al Maktoum, Vice President and Prime Minister of the UAE, ruler of Dubai has launched the Green economy for sustainable development framework back in 2012 that aims to reduce energy demands by 30% by 2030. As a part of this national agenda the Dubai integrated energy strategy and the Abu Dhabi vision 2030 were integrated with it. All those strategies and frameworks focus mainly on new buildings and their design techniques. Thus new green building rating systems were developed in order to control the process of designing, constructing and operating new buildings like the pearl rating system in Abu Dhabi and Al Saffat rating system in Dubai.

Despite of that very few actions were taken considering existing buildings and their energy consumption. Those buildings were designed and built before those actions for energy conservation were applied, thus they consume huge amounts of energy were most of this energy is considered wasted. Among 120,000 existing buildings in Dubai at least 30,000 existing buildings are considered with a high energy saving potential (S. Al Abbar 2015). Lately the Emirates Green Building council has launched a manual for retrofitting existing buildings that was prepared in collaboration with the ministry of public works and the supreme council of energy. This manual is not mandatory to be applied to existing buildings so promoting building retrofitting strategies among building’s owners is still considered as a huge challenge. Retrofitting those buildings is always an expensive process to be applied not to mention that in most cases it requires shutting down those buildings for a while till all renovations are accomplished.

This report is to choose an existing building in Abu Dhabi as a case study to be investigated in detail. Studying building use briefly, all existing services and their current situation then choosing one service to be studied separately in order to propose some solutions that help reducing energy consumption. Choosing the service to be studied will depend mainly on the feasibility of developing it with minimum implications on the building and its operational process in order to reduce building’s total energy consumption. Simple simulation will be run in order to test the proposed solutions and their energy saving potentials.

2 Case Study Building

2.1 Description

Hamdan center is considered to be one of the oldest building in the capital. The building was built back in 1976 and went operational in 1978. It was designed to be the first mixed used complex that serves the capital. Most buildings that were built in the same time were shut down, demolished and other new advanced buildings replaced them, and still Hamdan center is operating till the time being although it is suffering from serious technical
problems. It is located in the heart of Abu Dhabi’s CBD and it easy accessible from all the city’s attractions. In the middle of Hamdan Bin Mohamed Street about only 5 minutes away from Abu Dhabi Cornish the building lies covering an area of 5220 m² with a 100% coverage of the plot area. The building can be divided horizontally into two parts; podium that consist of ground, mezzanine, 1st & 2nd floors and four towers. Ground and mezzanine floors occupy 100% of plot area with no setbacks at all were 1st and 2nd floors have 2m projections from all sides as the building is surrounded by two major streets, a minor street and a parking lot. The four towers occupy almost 1/3 of the plot’s area.

![Figure 1: Accessibility map to Hamdan Center](image)

In the matter of building’s uses, generally both ground and mezzanine floors are dedicated for commercial retail shops. First floor is completely designed as an office space. Small area in the second floor was designed as a cinema or a theatre. This cinema hall was operating till 15 years ago when the management decided to shut it down due to regulatory complications with the local authorities. Late 2011 this area was redesigned as a department store and since then it is operating as a commercial space. The four towers A, B, C & D located on top of the podium were completely designed as residential apartments. Yet block D was completely separated from the building and has been operating as a hotel for more than twenty years and this is why it will be excluded from this study. The center is provided with sufficient space for its services and utilities. Three residential entrances are provided for the residential uses and other three servicing commercial and administrational activities in the podium. Other emergency exits are also provided with emergency stairways. Each residential tower is provided with elevators core, utilities rooms in each floor and servicing rooms on the roof floor. General maintenance and utilities rooms for the whole building are located on the ground floor as per the local regulations in the capital like transformer, electric, fire pumps and generator rooms.
Figure 2: Ground floor plan

Figure 3: Mezzanine floor plan

Figure 4: First floor plan

Figure 5: Second floor plan
2.2 Available Services

Hamadan center was considered as a very unique building in the matter of the services that were implemented in it. Although it was built in 1976, yet it is the first building in the capital to adopt the central HVAC technology and the first to use water chillers in that system. Back in time, the building was considered as one of the most advanced buildings in the region. All critical services were implemented in it; HVAC, lighting, water supply, drainage, firefighting, vertical transportation and low current systems. For more than 38 years the building went through major challenges like proper maintenance and continues changes in the local regulation in the capital. Many changes and modifications were done in order to comply with the latest building codes applied in Abu Dhabi. Other changes took place as a must to keep building services in an acceptable condition.

Going through building services briefly; they can be divided into two categories. The first is the major ones; HVAC, drainage and water supply. Through site visits and investigating maintenance reports; those three service are suffering severely. When analyzing building services, the building was divided vertically rather horizontally, meaning that activities were completely ignored in the services design. For the HVAC system, the building is serviced by 15 chillers in total; four dedicated for block A, four for block D, two for block B, two for block C and extra three servicing common area between block B & C. The four servicing block D were replaced twice during the past 20 years. Those servicing both block A and block B were replaced once in the early 90s and they have been operating since then. Were the ones servicing block C and the common area were replaced late 2013. From a rough comparison, the difference in energy consumption between the old chillers and the new ones is remarkable. For FAHUs dedicated for the commercial spaces they were replaced few years back and they have been operating and maintained well since then. Finally, for the AHUs they were neglected for a long while but the current management has a plan to change all units while changing tenants. The severe problem in the cooling system is the chilled water network. This network is very long and no proper maintenance was done to it for many years. Pumps and tanks are maintained well as they are easy accessible but the piping network needs an immediate change in some parts of it. Many of those pipes are worn out and are supported with steel beams in order to keep them in place.

Moving to the drainage system; again pipes condition is very bad. Leakage was spotted many times in different places in the building. Minor solutions were implemented just to handle the problem in the short term like changing some accessible pipes or connections but the more the problem is ignored, the more severe it gets. The water supply network faces the same problem as the drainage system and again no serious actions were taken to solve the original problem rather than some minor acts for fixtures and appliances changes. The main issue with those three is that they will require full or at least partial shutdown for the building for relatively long time. And this is not acceptable by the building owners at all as it is a huge loss to them. Moreover, the cost of undertaking such an action is very costly and requires a very accurate plan.

The other category is the minor services, yes they are not minor in importance but they require an easier maintenance plan than the ones mentioned above. This category includes firefighting/fire alarm, vertical connectivity system, electrical systems both light & power, low currents systems and CCTV. In the matter of the firefighting/fire alarm systems, they are relatively new as they were not included in the original building design. Those systems were implemented later in order to comply with the local regulation applied in the emirate of Abu Dhabi. Smoke and heat detectors, fire alarms, hose reels and fire extinguishers are distributed as per the applied fire code NFPA 5000. A dedicated room
for the fire water pumps and the fire water storage is mixed with the domestic water in three underground water tanks. Three fire pumps are placed; one main electrical pump that starts when a certain alarm is on, another electric is there as a stand by and a large diesel one that is considered as an emergency pump in the case of electricity cut offs. It is important to mention that no sprinkler system is implemented as it is not a mandatory requirement for this type of buildings.

In the matter of vertical connectivity, this service includes elevators and escalators. Only two escalators are provided connecting ground and mezzanine floor of the commercial area only. One elevator provided for offices in block A linking ground and first floors only and two are provided for Block B offices linking ground, first and second floors. Block A residential tower is serviced by two elevators linking all its floors going through 18 floors up to the roof. Same elevators are dedicated for the hotel. Other three elevators are dedicated for both blocks B & C reaching to the roof through 14 floors. Machine rooms of the residential elevators are located on the roof of each block were those for podium elevators are located on the roof of the podium. All elevators machines, cables and mechanical parts were changed few times through building life. Still elevators cars were never changed and they need immediate attention.

The electrical systems in the building that includes both power and light systems; both are presented in the building but again of an outdated technology. For the power connections, the building complies with the local regulations in that matters; three pins power sockets are distributed everywhere in the building. Still a problem was monitored that current tenant’s needs for both offices and residential uses are higher than the numbers of sockets available in the buildings. The lighting system is very primitive in the building. Land uses and activities were completely ignored when designing this system. Equal distribution of lighting fixtures and appliances was done for all uses of the building. For example, one lighting point was placed in every bedroom and only two in living areas. In the past those points were used by incandescent light bulbs now those were replaced by compacted florescent bulbs. Still, those points are not enough for activities taking place in those space. Same strategy was applied for the office spaces as they were designed as an open space that is to be divided later in accordance with tenets requirements. This homogeneous light distribution resulted in poor light levels in some areas and very bright spaces in relation to the activities taking place in those spaces. Finally, electric rooms were provided in each floor as per the local regulation. Separate electrical rooms for elevators, chillers controls and water pumps were also provided. All those electric rooms are directly connected to the main one in the ground floor.

3 Selected Service for Analysis and Development
Considering the analysis of the existing services mentioned above, this report is to select one of them to be studied and improved in detail. In the matter of importance, the HVAC system including the chilled water piping network comes first followed by drainage system and the water supply. Rust and corrosion spread everywhere in those pipes and minor maintenance procedures are not enough anymore. A major maintenance plan should be applied at the earliest but this will require shutting down the building which can be done on a phasing plan. Still this will result in evacuating parts of the building and this the owners cannot accept in the time being. The firefighting/fire alarm system is relatively new and is maintained properly as the Abu Dhabi Civil Defense department (ADCD) checks it on an annual basis. For the low current system and CCTV, they are all up to date in order to meet tenants’ needs. Finally, the electrical systems specially lighting system sounds to be the most appropriate service to be upgraded in the building, considering all implications resulting from other systems. The lighting system in the building has no design standards,
applying some basic design strategies to it alongside some of the modern technologies in this matter can result in huge improvements in performance and major savings in the matter of energy savings.

3.1 Existing Situation of Lighting System

Lighting system has huge impact on users of the space and their attitude. In many cases, designers deny this important fact and go for a homogenous design that does not differ between the activities taking place in the space under design. That was the case in Hamdan Center, very primitive design was provided with very limited lighting fixtures and appliance. For example, in residential units' bedrooms have only one ceiling light outlet while living areas has two of them. Years back, incandescent light bulbs were used in for those spaces but nowadays they are replaced with compacted florescent bulbs. For bathrooms and kitchens single florescent tubes are used as a task light and one compacted florescent 20 cm dia spot is placed in the ceiling. For commercial areas and offices 60*60 florescent units that contain four T8 tubes are distributed to a certain module to allow flexibility of re-dividing those spaces as per tenant’s needs. In office spaces incandescent spots of 50 mm dia were used as decorative elements but many of them are damaged and not operating anymore. Lately, LEDs were added in common areas like corridors and stairways. Those installed in the emergency stairways are provided with motion sensors to light up only when one emergency doors in any floor is opened and when there is any motion in the stairways.

3.2 Possible Improvements and Their Feasibility

Possible improvements to the lighting system can be divided into two categories; the first is redesigning the light distribution for all spaces in the building without neglecting the daylight factor. In fact, counting the daylight in such a design can result in huge savings in the matter of energy consumption taking in consideration that the building is standing alone in the area. The fact that residential towers are occupying only 1/3 of plot’s area providing daylight for all apartments and all livable spaces inside them. Redesigning process should take in account type of activity taking place in each space to provide enough light levels with no wasted energy. The second category is using innovative and modern lighting technologies like dynamic lighting techniques and new energy saving light fixtures and appliances.

Undertaking such improvements and development is very feasible compared to upgrading other services in the building. Again upgrading plans are relatively simple as all they need is an accurate design, very limited budget, they do not require shutting down the building or evacuating it and finally this process can take place on different phases. Minor disturbance can happen as upgrading process for both commercial and offices can be done in night time while those spaces are closed and not used. For the residential units, this can happen while the unit is vacant or before new tenants are moving in. Taking in consideration that Abu Dhabi distribution company (ADDC) has lately changed all power meters into advanced ones that can separate readings from different services, then it will be easy to track consumption rates to document savings achieved.

4 Suitable New Technologies

Lighting technologies are not some new appliances that will be replaced to improve the quality of light levels, it’s a comprehensive design that appliances or fixture take a small part of it in order to meet design objectives or in other words it is the perfect combination of art and science. So before going into more details about the current technologies of the appliance and fixture, a brief of lighting design should be elaborated in order to justify why those technologies were used in that particular space. Design process has some design
barriers in order to achieve the required results. First, type of the space under design should be identified in the matter of the activity taking place in it as certain light densities are defined by ASHRAE codes and design guidelines.

<table>
<thead>
<tr>
<th>Building Area Type</th>
<th>Lighting Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditorium</td>
<td>10</td>
</tr>
<tr>
<td>Convention Center</td>
<td>11</td>
</tr>
<tr>
<td>Court House</td>
<td>12</td>
</tr>
<tr>
<td>Dining: Bar Lounge/Lounge</td>
<td>13</td>
</tr>
<tr>
<td>Dining: Cafeteria/Fast Food</td>
<td>14</td>
</tr>
<tr>
<td>Dining: Family</td>
<td>15</td>
</tr>
<tr>
<td>Dormitory</td>
<td>16</td>
</tr>
<tr>
<td>Exercise Center</td>
<td>17</td>
</tr>
<tr>
<td>Gymnasium</td>
<td>18</td>
</tr>
<tr>
<td>Healthcare-Clinic</td>
<td>19</td>
</tr>
<tr>
<td>Hospital</td>
<td>20</td>
</tr>
<tr>
<td>Hotel</td>
<td>21</td>
</tr>
<tr>
<td>Library</td>
<td>22</td>
</tr>
<tr>
<td>Manufacturing Facility</td>
<td>23</td>
</tr>
</tbody>
</table>

The designer should know how to achieve the required light levels by type of lighting and how many watts per meters square will be achieved from each source of light in the space. Possible light sources in the space under design are; daylight, task light, general artificial light source. Controlling each type of those sources will develop the best practice for the space. Then the turn for modern technologies in the matter of light sources, dimming fixtures, lighting control, motion sensors and dynamic lighting systems come to take place. Each part of the lighting system has developed significantly over the past few years.

4.1 Description of Technologies

- Integrating Daylighting.

Allowing daylight inside the space is thought to have many health and aesthetic benefits on space users especially in offices, schools and hospitals. Certain levels of daylight can result in huge savings in the matter energy consumption from both artificial lighting required and HVAC loads. In many artificial lighting systems there would be some energy from light sources that will be wasted in the form of heat and this result in increasing the cooling loads required to cool the space. It is thought that energy savings vary from 15% to 40% in building overall consumption when integrating daylight in the lighting systems. Not to mention other psychological benefits on the attitude of space users as daylight is thought to enhance the productivity of employees and students.

Still, this strategy has some disadvantages; in hot climates this can result in a huge heat gain from the outside that will require huge cooling loads and glare issues depending on the light levels reaching this space and this can be managed by blinders. These two challenges can be solved by new lighting controls systems that will be discussed later.
- Artificial Lighting Sources.

The current lighting bulbs used in the building are very limited; compacted florescent (CFLs) and T12 florescent tubes in residential units, four T8 tubes unit and incandescent spot lights in office and commercial spaces, LED 20 cm dia spots are placed in common areas like corridors and stairways and the final ones were placed in the building lately. When deciding to change types of light sources in a certain space will require the designer to be familiar with some lighting parameters or characteristics; color temperature, luminance, luminance uniformity level, luminous efficacy, maintenance factor, unified glare rating (UGR) reflection factors and reflectors design. New advanced computer software made the process of calculating those parameters in the space much easier than before. DIALux is one of those advanced software that contains a huge database of the latest products in the market, all the designer has to do is just to choose type of light sources and its distribution through the space and the software runs the simulation and produces a report containing all required calculations. Upon this report designer makes the decision to change type of light, its number or its distribution in the space. Other parameters should be specified by the designer such as finish materials, working levels and definitely the geometry of the space. Energy savings from this retrofit procedure can start from 15% up to 50% depending on the type of appliances selected and the size of the retrofit plan. Another important aspect of selecting a certain technology in the matter of light sources is internal component of the appliance itself. It is thought that florescent and LEDs are the best two technologies nowadays, still the technical parameters of their internal components and ballasts should be addressed to help making the right selection. Average lifetime (operating hours) of the light source and the life cycle of its components are also important considering the level of maintenance required of them and their future disposal process.

<table>
<thead>
<tr>
<th>Type of lamp</th>
<th>Luminous efficacy range (lm/W)</th>
<th>Average lifetime (working hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent lamps</td>
<td>15 – 1500</td>
<td>750 – 2,500</td>
</tr>
<tr>
<td>Halogen (240V)</td>
<td>10 – 75</td>
<td>2,000</td>
</tr>
<tr>
<td>Halogen (6V - 21V)</td>
<td>30 – 50</td>
<td>2,000 – 4,500</td>
</tr>
<tr>
<td>T12 linear fluorescent with magnetic ballast (Conventional)</td>
<td>60 – 70</td>
<td>6,000 – 8,000</td>
</tr>
<tr>
<td>T8 linear fluorescent with electronic ballast</td>
<td>80 – 100</td>
<td>18,000</td>
</tr>
<tr>
<td>T5 linear fluorescent with electronic ballast</td>
<td>70 – 104</td>
<td>18,000</td>
</tr>
<tr>
<td>Compact Fluorescent Lamps (CFL)</td>
<td>50 – 70</td>
<td>10,000</td>
</tr>
<tr>
<td>LED lamps</td>
<td>3 – 4,2</td>
<td>50,000</td>
</tr>
</tbody>
</table>

Figure 7: Benefits of correct lighting (QG 2010)

A simple comparison between two types of bulbs and ballasts of the same technology was presented in the technical guidelines for retrofitting existing buildings 2015 stated that a total of 50% saving potential was recorded only by changing a T12 65W florescent tube with a 13W control gear into a T5 35W florescent tube with a 4W control gear taking in consideration the same readings for lighting parameters.

- Advanced Lighting Controls.

The latest technology in the field of dynamic lighting techniques is light controls. The concept is not new at all, lighting controls has a long history but it witnessed huge improvements in the past few years. The fact that huge amounts of energy is wasted
because of the inefficient behavior of space users like keeping lights switched on when the space is unoccupied has resulted in developing the idea of motion sensors. Those sensors have spread virally over the past decade as they switch off lights once the space is unoccupied. Now the same concept was developed but in a more innovative way. Sensors were developed to read certain lux levels inside the space. This technique can enhance the use of daylight as sensors will keep all artificial lights off as long as the daylighting maintains certain levels of lux inside the space. Once lux levels start to drop below those levels sensors will switch on artificial light sources in a certain hierarchy just to remain the lux level the same. Energy consumed by those sensors are minimal compared to the amount of energy saved due to this intelligent system. The development in this filed is unstoppable, new sensors were introduced that can control movable shading techniques in order to control the amount of daylight allowed into the space. Those sensors have overcome the disadvantages of day lighting such as heat gain and glare issues.

Light controls systems are more broad than just those advanced sensors as they include light on/off dimming controls, light fitting that are suitable to operate with those sensors and building management systems that can control and monitor the light control system. In a simple retrofitting strategy, a normal lighting fitting can be changed with a new one that include motion or lux sensor so it can switch light on or off as per the lux level or occupancy in the space. Those light fitting do not require major changes in the existing lighting network, only replacement of the light fitting and its ballast. Other fully integrated lighting control systems using advanced automation protocols like Digital addressable lighting interface, (DALI) or the Konnex (KNX) can be integrated in a retrofitting plan but they will be very expensive to be applied and this is why they are preferable in new buildings or developments.

4.2 Retrofitting Measures
A comprehensive plan should be designed to achieve acceptable energy savings not only a certain, standalone technology. Taking in consideration that the building under design has the minimal saving fittings and it suitable to apply a combination of actions not only one. The cost factor is very important in such a case; some technologies can provide higher saving rates but their cost will make the payback period for them too long. A balanced study between the targeted savings and their cost should be developed before making the decision to undertake those action or strategies. Another key factor is the procedure of applying those strategies and their technical requirements. Can those strategies be done over several phases, can they be developed while the building is running or will they require shutting it for a while, will they require replacing major parts of the lighting network like cabling and wiring or will they just require changing ballasts and fittings and so on. The main criteria here was to avoid any plan that will require shutting down the building or even parts of it, elsewise all possible strategies can be accepted within a decent budget. The following list of actions and strategies that should be applied in respect to the conditions mentioned above.

- Fitting Replacement.
Remove all halogen and incandescent lights even if they were only for decorative purposes. Still they can be replaced by LEDs or CFLs. Replace all 60*60 florescent reflectors units with LED HF that give the required lux levels. Finally change all T12 or T8 florescent tubes to T5. Testing the results of those replacements can be easily tested via DIALux and energy consumption will be produced in a report that can be later compared with the current consumption. Appendix B has a list of proposed light fittings that are considered to be some of the most popular types used in the UAE market. Those selected
fitting are suitable to replace all the existing fittings with a better average lifetime and a better energy saving potential.

- **Motion Sensors.**
  This action has already started but it has to be generalized over all public spaces, utility rooms and facilities in the building. Toilets that serve the commercial and administrative uses have their lights on 24/7 although they are unoccupied most of the time. The same can be applied to all corridors and common areas in residential towers.

- **Lux Levels Sensors.**
  Adding those sensors in all commercial and administrative space in order to enhance the use of day lighting. Manual blinders can be added and controlled by space users in order to eliminate the heat gain during summer months and to reduce glare issue. Those sensors are a must in such activities as users’ behavior tend to be irresponsible to the matter of energy savings and in many cases some offices do leave lights switched on overnight.

- **Light On/Off Dimming Controls.**
  These controls should be applied in residential units for all livable spaces in order to control lux levels manually as per the occupancy or the need of tenants.

All those actions require only replacing the fitting, control gear and ballasts with no further changes to the lighting network in the matter of special wiring or cabling required for them. The first strategy will be tested in detail below supported with simple simulation via DIALux.

### 5 Expected Improvements and Savings

Any retrofit plant to take place to such a building should be investigated and tested over certain aspects; its function and operation, energy savings achieved from it, its future maintenance procedures, cost and financials and its impact on other building services. DIALux software was selected to test the proposed light fittings replacements. Designer has only to select the right activity for the space under design and the software will automatically consider the standard lux levels for this activity. The design report produced at the end of the simulation will show the proposed lux levels as per the selected light fittings compared to the standard levels. The report will document energy consumed by each fitting and finally the total consumption for this space as per the provided working hours. A simple office space with the size of 4.2*4.7 m will be chosen to redesign light fittings in it and check possible energy savings achieved in relation to lux levels, cost and average fitting lifetime. Design parameters will remain constant such as, space geometry, operating hours, wok plan level and finishing materials. Existing light fittings in the space are as follows; 4 units of 60*60 reflector units with four T8 florescent tubes and 12 incandescent spot lights with 50 mm dia. The design will consider removing all those fitting and replace them with a very popular LED fitting in the UAE market. Only 6 units of OMEGA LED 4000 HF L830 297*1197 will be used in this space with no further spotlights or task lightings.

#### 5.1 Function

Design light density defined by ASHRAE code and the ADIBC should be respected. The fact here that those standards are not respected in the current status of the office. Tenants tend to change light fittings on their own without referring to the building management and this should be stopped when applying the retrofitting plan as the building management has to keep a record for every change that take place in the building. The proposed light fittings meet the standard for lux levels and provide a better lighting condition in the space.
5.2 Energy Savings

Unfortunately, accurate energy savings cannot be measured here as there are no specific consumption rates for each space by itself, still savings can be at least calculated. Running DIALux simulation for each space inside the unit either residential, administrative or even commercial will give the total connected load for this space individually. Summing up all those loads will give the total load for this unit considering the new light fittings in it. Comparing this load to the latest electricity bill for the same unit will give an estimation for the savings that could be achieved from this retrofitting plan. The space used for the simulation is very simple compared to a whole unit design but taking all units for possible replacements to all light fittings in the building will result in huge savings. Loads calculated from this simulation were 13.24 W/m² for an area of 20.12 m². For the whole office area which is 150 m² with the assumption of using the same light fitting used in this simulation only the total load will be around 100 W/m². This office is considered to be one of the big
units in the building, so taking the fact that the minimum electricity load recorded for a unit is 600 kWh and the maximum is 1200 kwh then it can be assumed that the load for this office is 1200 Kwh. The lighting system part of this load can be calculated as 15% of the total load, it would be around 180 kwh = 248.4 W/m² taking in consideration that the kwh is calculated on a monthly basis. From the above calculation the total savings will reach around 40%.

5.3 Maintenance
LEDs have the higher average lifetime which can be represented as operating hours among all other light fittings. In other words, maintenance procedures are minimal compared to CFLs or normal florescent tubes. Another aspect of the maintenance procedure is applying maintenance as replacing a new fitting has the minimal implications on space users and it can be done during working hours with the lowest disturbance to users.

5.4 Impact on Other Services
Impacts on other services can be divided to both negative and positive ones. In the matter of positive impacts, they can be clearly witnessed in the HVAC cooling loads. LEDs and CFLs have the lowest energy losses that are presented in the space as heat. This will help reducing the cooling loads leading into more energy savings. No major negative impacts over other services and they tend to be the perfect replacements for all other types of light fitting in any type of buildings.

6 Conclusions
Lighting system in a building may sound easy to be retrofitted, updated or even replaced, still it has huge impacts in the matter of energy savings. In some cases, like the building under investigation here, the lighting system sounds to be the best to be retrofitted with a possible budget and less implications on either other services, building users or even building management and owner. All new studies and researches have stated that the future in the field of light fittings is for LEDs and CFLs as manufactures do not stop developing them. Everyday a new product is released and introduced to the market that overcomes minor disadvantages in the previous model. It is never too late to shift to those modern technologies as the replacement procedures is quite simple compared to other building services. Taking the action to a further level, different types of sensors either motion or lux levels sensors will add more to the savings recorded. All those strategies are good enough to achieve decent savings without any interference from building users. Still awareness plans should be introduced to tenants advising them with the right energy savings actions that they should apply in their lifestyles. Moreover, operation manuals should be designed, printed and delivered to each tenant that moves into the building. Light control systems are of greater benefits if applied in integration with the fitting replacements. Still there is a certain level that those systems can be applied to an existing building depending on the current situation of the building.

Finally, this study was developed to prove the feasibility of undertaking lighting system retrofitting plans to a very old building in the UAE. The selected retrofit strategies are considered very simple to be applied in a decent time frame with an acceptable budget and the minimal disturbance for building users and management, still they can achieve remarkable energy savings in the matter of electricity bills. The case of Hamdan center can be generalized to all buildings of the same current situation and this will result in huge savings in the matter of power produced and delivered by the government.
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Abstract: Building envelopes under hot climates face a major design challenge that requires balancing daylight admission, heat control and aesthetical considerations. Inadequate design often results in overheated spaces that rely extensively on energy intensive mechanical systems to provide comfort. As a first response, conventional fixed shading devices have been widely used to control heat gain and glare. However, they face many limitations; such as their inability to move or be controlled in order to adapt to the changing external conditions. Active shading systems have been developed to counter such limitations. Active shading systems may be best categorized in three main types; smart glazing, kinetic external shading systems and renewable energy systems integrated to active shadings. This study focuses on the kinetic external shading systems because of their flexible adaptation to the extreme hot climate needs and requirements. This paper focuses on two main types of kinetic external shadings; the rotating and the folding shading systems. An extensive critical literature review was carried out to establish the status of knowledge of these two systems, where the function and the building application for each system were explored. Furthermore, limitations and future opportunities of the systems were identified. The review highlighted high integration opportunities for their on the extensively glazed buildings in the UAE, yielding multiple benefits such as reduction in the heat gain in buildings, in lighting and cooling loads, in energy consumption in the building and ultimately the energy cost.

Keywords: Kinetic shading systems, folding, rotating, challenges, opportunities, hot climate, UAE
1 Introduction

The Gulf Cooperation Council (GCC) region has one of the world’s highest rates of urbanization levels (Ramadan 2015). Urbanization was driven by the increased population resulting from internal migration and the flow of expatriate workers that were attracted to the economical activities and employment opportunities. Additionally, urbanization was fuelled by the oil discovery, business, services and ambitious projects. Similarly to other GCC countries, the United Arab Emirates (UAE) has experienced high rates of urbanization, with the current urbanization reaching 85.5% of the total population compared to 83% in 2011 (CIA 2015). Consequently, the building sector in the (UAE) has experienced a tremendous expansion in the last forty years due to population growth and economic development.

The UAE has focused on different kinds of construction, such as the high rise commercial buildings, private residential developments, mass housing, commercial and public services infrastructure. A lack of energy conscious building regulation during the urbanization growth resulted on the UAE becoming one of the highest per capita energy consumers in the world (Khondaker et al. 2016). Energy consumption in the UAE has been increasing at an annual rate of 4% over the past six years. It is predicted that this increase will reach up to 5% by 2020 (Khondaker et al. 2016). Studies have shown that the energy needed for cooling the buildings in the UAE was about 60–75% of the total building electricity consumption (Radhi 2009; Aboulnaga 2006). Fully glazed buildings for different uses including housing are dominant features of Dubai and Abu Dhabi skyline (Figure 1).

![Figure 1: Abu Dhabi and Dubai Skyline with extensively glazed buildings (Source: left, Wikipedia Commons (2013a), right, Wikipedia Commons (2010)).](image)

Glazing in some buildings i.e. mass housing and commercial buildings can reach up to 80–100% (Aboulnaga 2006) (Figure 2). The UAE is known for its extreme hot climate with very high temperatures in summer reaching up to 50° Celsius during the day. It has been widely verified that the use of extensive glazing in buildings in the UAE allows unnecessary heat gain and glare (Aboulnaga 2006; Radhi 2009; Radhi et al. 2013; Taleb 2014), overwhelmingly calling for protection against overheating and sun glare in summer.

Heat and glare control are critical factors in glass structures. Consequently, approaches that control heat and glare while still admit the needed daylight is likely to be the most relevant solutions. The use of devices and technologies to control and improve the current performance of glazed buildings is a step towards saving energy and reducing cooling loads while creating comfortable environments. In this regard, advanced glazing and solar control technologies, double skin facades and shading systems are useful.
strategies that can be applied to highly glazed buildings (Radhi et al. 2013; Taleb & Musleh 2015; Hammad & Abu-Hijleh 2010). The use of external shading that responds to external environmental conditions in such contexts is a traditionally accepted mean of heat and excessive daylight control. These however carry limitations that are addressed in the active shading ones. Kinetic shading devices are one of the strategies that insure the balance between sufficient daylighting levels and solar protection throughout the variable day conditions and ultimately improve energy efficiency in the building.

Figure 2: Mass Housing in Dubai (left: Al Shiata Housing Tower, source: (WIKIPEDIA COMMONS (2008), right: Sowwah Square Residential Building, source: (WIKIPEDIA COMMONS (2013b))

In this regard, this paper aims to critically review the potentialities and limitations of a specific active system: the kinetic systems and their applicability in different building type in general and housing in particular under the hot climate of the UAE.

2 External Shading systems

External shading devices are used in buildings with a potential direct contribution to provide a healthy balance by reducing the excessive glare and heat gain while contributing to lower energy used in air-conditioning, as well as provide privacy (Stack et al. 1999). External shading devices were known for their simple, low-cost solution to control excessive amount of sunlight (Gugliermetti & Bisegna 2006). Several studies were done on the performance of external shadings systems applied as diverse responses to different climatic conditions (Palmero-Marrero & Oliveira 2010), while other studies have shown their role in improving daylighting levels inside buildings (Freewan et al. 2009; Dubois 2003). Some studies showed their contribution on energy saving in buildings (Alzoubi & Al-Zoubi 2010; Corrado et al. 2001). External shading systems may be categorised under passive and active shading types.

2.1 Passive shading system

Passive shading systems are static devices that do not involve any movement, and are designed to protect the building from heat gain and excessive daylight within specific conditions (Olgyay & Olgyay 1976). The conventional passive shading devices used in buildings include external roller shades, overhangs, venetian blinds and internal shading (Kirimtat et al. 2016). They are often classified principally according to their placement, whether it is fixed internally or externally.

The design challenge often resides in reconciling conflicting requirements i.e. control daylight, glare and heat gain, while maintaining a view out (Aldawoud 2013). Hence, the technological response through the development of alternate solutions such as the smart glazing technology, smart, dynamic, external or internal shading devices with sensors and control systems.
2.2 Active shading system

The above limitations of passive shading devices have driven a quest for dynamic solutions that respond throughout the day to the varying external conditions with increased comfort and energy efficiency (Kensek & Hansanuwat 2011, Drozdowski 2011). Furthermore, active shading systems tend to benefit the occupants’ comfort and are sometimes used to generate electricity. Since the kinetic systems were introduced in buildings, their use was mainly to control four major factors: daylighting control, solar thermal control, ventilation control, and energy generation (Lee & Selkowitz 1997).

There are different categories of active systems that were developed to control daylight and heat in buildings, but can be classified into three types (Figure 3). Windows with dynamic optical properties is the first category of active systems. Smart glazing is defined to have light transmission properties that are altered when voltage, light or heat is applied, by changing from translucent to transparent (Lampert 1998). There are several types of smart glazing used in buildings such as the Suspended Particle Devices (SPDs) (Baetens et al. 2010), Electrochromic Devices (Kraft & Rottmann 2009) and the Liquid Crystal Devices (Lampert 2003). Studies have claimed that 50% energy reductions can be achieved from smart glazing systems over conventional glazing (Papaefthimiou et al. 2006). However, their cost is high and they require more maintenance than the conventional shading systems. Additionally their durability and life cycle still needs to be improved (Piccolo & Simone 2015).

The second category of active systems integrates renewable energy in the shading devices, where the benefit is higher since it can be used as a source of producing electricity, heat and acting as a shading device (Hwang et al. 2012). Two types of shading systems fall under this category: Photovoltaic Panels (PV) and algae facade system. PV panels can be integrated with external shading devices as Building Integrated Photovoltaic’s (BIPV) and produce electricity and shade the building (Yoo & Manz 2011). However, there are some limitations in using PV panels in shading devices; dust accumulation and limited tolerance to overheating usually restricts the expected performance, lower the efficiency and decrease the power output of the PV panels in hot and arid climates (Patt et al. 2013). Additionally, when the temperature increases it leads to reduction in the efficiency of the PV panel (Kumar & Kaur 2014). The other type which is the Algae facade system acts as a dynamic shading device that generates heat and biomass as a renewable energy source to be used by the energy services in the building (Kim 2014). The limitation in the system is the high cost, where the square meter for the single bioreactor system runs currently around $2,500 (Wallis 2013).
The kinetic shading systems represent the third category and are based on movement in response to external environmental changes (Sharaidin 2014). There are two types within this category; the rotating and folding shading systems. This type of active shading system is reviewed in this study due to its ability to adapt to the external environmental conditions which is critical in the case of hot climate in the UAE.

3 Kinetic shading system

Kinetic shading systems are defined by their ability to move through geometric transformation that affect the changing state or material properties or physical structure of the shading system (Sharaidin 2014). Their properties can change in response to exterior climate and interior needs. They also control glare and the sunlight penetration in the interior spaces (Lee et al. 2004). The development of kinetic shading systems was a response to the growing need for energy reduction in buildings, whereas previously façades were static (Harrison et al. 2005). Kinetic shading technology balances indoor environmental quality (IEQ), such as; discomfort glare, view to outside, privacy, thermal comfort and air quality (Wigginton 2002). The mechanism in the kinetic shading depends on mechanical, chemical and electrical engineering where rotating, folding, sliding, expanding, shrinking and transforming in the shading devices take place (Fox & Kemp 2009; Asefi 2010; Moloney 2011). There is a potential in the application of the kinetic shading systems in mass housing in the sense that usually occupants adjust their movable shading according to their needs; blocking the heat or increasing daylight. In this case, kinetic shading systems can contribute to an increased comfort as well as energy saving.

There are two types of kinetic shading systems that are suitable for hot and arid climates such as the UAE’s; the rotating and the folding shading systems (Cellai et al. 2014).

3.1 Rotating Shading Systems

Rotating shading systems are used in building facades as shading devices that are triggered by mechanical or electrical transformation that takes place in response to an external environmental condition, or to occupants' needs (Orsi 2009). The system is
designed to rotate around either a horizontal or vertical axis depending on the position of its slates (Orsi 2009). Kensek & Hansanuwat (2011) analysed the performance of rotating overhang and horizontal louvers in terms of the energy savings for cooling and heating. The results showed that both systems were able to rotate 90 degrees, and decreased the energy consumption by 33% for cooling and 30% for heating.

Hammad & Abu-Hijleh (2010) explored the influence of external dynamic louvers with light dimming strategies on the energy consumption of an office in Abu Dhabi. The results showed that the dynamic louvers with angle of −20° for the south had 30.31% energy savings, while with a 20° angle for the east and west orientations the savings were 34.02% and 28.57%, respectively (Hammad & Abu-Hijleh 2010). Similarly, a study tested a new double skin façade with movable integrated shading louvers to define its energy performance. The results showed that during the entire year the proposed façade significantly improved the building energy behaviour, especially when the winter configuration forced convection was considered (Baldinelli 2009).

Rotating shading devices can be made from different materials; glass, metal, fabric, wood or aluminium. A study was done on glass rotating system called glass lamellas, where a prototype of light redirecting glass lamellas with a solar control surface was built. Measurements of daylight in the laboratory on overcast days showed that the shading device improves the daylight distribution in the building when the glass lamellas are rotated 30° outwards with the reflective surface upwards (Laustsen et al. 2008). The result was compared with traditional static opaque shading device and it showed that the glass lamellas had better utilization of daylight (Laustsen et al. 2008). Similarly, a study by Appelfeld & Svendsen (2013) indicated that the use of rotating glass lamellas improves the distribution of daylight within the space.

In the UAE, fabric rotating shading devices were applied in Hazza Bin Zayed Football Stadium in Al Ain, UAE. The envelope has about 600 rotating shading panels that were designed to allow passive cooling in the stadium by shading the building during the day while allowing fresh air to flow as well as enhancing growth of the natural grass (Archdaily 2015). The shading systems rotate around a horizontal axis in response to the changing angle of the sun (Figure 4).

The existing literature establishes that rotating shading systems can be applied in different climatic zones, including harsh climates such as the UAE’s and make a
remarkable contribution in energy saving and improving the internal environment in buildings. Table 1 illustrates some building applications along benefits.

**Table 1: Application of rotating shading systems in buildings**

| Building/Context | European Commission Headquarters, Brussels  
| Source: (Colt 2016a) |
| --- | --- |
| **Building Application** |  |
| **Material** | Glass rotating shading system  |
| **Description** | The façade was renovated using glass rotating systems which responds to the changes in light intensity and temperature. It is a solar controlled glass with high reflectance coatings.  |
| **Benefits** | Reduces solar heat gain and cooling loads. Primary energy consumption of the building was reduced by 50% lower than a similar building as modelled. Views are available when glass louvers are used. Can be used in residential buildings and mass housing.  |

| Building/Context | Zurich Airport, Switzerland  
| Source: (Colt 2016b) |
| --- | --- |
| **Building Application** |  |
| **Material** | Metal rotating shading device  |
| **Description** | Perforated metal rotating shading system was used in Zurich airport to reduce the extensive use of glass over the large area to avoid excessive heat gain within the building. The system rotates in response to changing climatic conditions and available daylight.  |
| **Benefits** | Reductions in cooling loads and glare. Can be used in residential buildings and mass housing.  |

| Building/Context | Office building, Canada  
| Source: (Grozdanic 2014) |
| --- | --- |
| **Building Application** |  |
| **Material** | Wood rotating shading device  |
| **Description** | Penumbra kinetic shading system was designed to rotate in three directions in response to the sun’s position. The vertical louvers rotate in three directions, both laterally and axially, and can independently pivot to maximize solar protection.  |
| **Benefits** | Aesthetical kinetic appearance for the building. Reductions in cooling energy and glare from direct sun light.  |
3.2 Folding Shading Systems

Another effective type of shading is the folding shading system also called the shape morphing solar shading or the Origami shading device. This type of shading has been applied in several engineering fields; as adjustable and reconfigurable structures, folding geometries have also been used in biomedical devices (Kuribayashi et al. 2006) and, in space and aircraft applications (Nishiyama 2012). However, in architecture the use of folding shading is mainly experimental, especially when used as a shading device. When applied on buildings, they usually have different typologies of movement such as; translation, rotation and scaling, where external forces are required. Recent trends in shading device have tried to replace traditional mechanical systems with multifunctional and smart actuators (Addington & Schodek 2005).

Smart materials are often used in adaptive structures where change is needed. Sensors analyze the variation of an external stimulus and transfer the information to the actuator, which in turn, provides the structure with a change in one of its properties. Smart material is a material that changes one of its properties in response to an external stimulus and combines both sensor and actuator functions (Otsuka & Wayman 1998). The movement of the folding shading systems has two main typologies (Fiorito et al., 2016):
- Translational movement which performs a bi-dimensional change of shape; it is linear and allows adjustment levels in the building skins by size-opening variation and by overlapping layers.
- Rotational movement which performs a tri-dimensional change of shape; and performs swivel motion both in the same axis and/or around a different axis.

In both typologies an actuator is required, and it can be completely embedded into the device or strategically located to trigger a specific action.

A folding shading system was applied in Al Bahar Towers in Abu Dhabi in the UAE consisting of two high rise commercial towers (Figure 5). The dynamic façade in Al Bahar Towers was designed to achieve privacy, reduce glare and heat gain (Boake et al. 2014). The façade consists of a series of semi-transparent umbrella-like structures that are triggered by heat source provided through electrical current to open and close in response to the sun’s path. This design resulted in glare reduction, balanced daylight, less artificial lighting use, and over 50% reduction in heat gain, which is projected to reduce CO2 emissions by 1,750 tons per year (Boake et al. 2014).

Another design of folding shading system was applied in Al Doha Tower in Doha, Qatar (Boake et al. 2014). The shading system consisted of four “butterfly” aluminum elements of different scales that represent Mashrabiya. The purpose of the system is to protect the building from excessive sunlight and heat gain. The shading system is expected to reduce cooling loads by 20% (Boake et al. 2014).
There are other types of folding shading systems that can be applied in buildings. They usually move in response to variable external conditions, and they have the ability of minimizing energy required to perform adaptation. Table 2 illustrates a sample of different typologies of folding shading devices applied on buildings.

<table>
<thead>
<tr>
<th>Application / Name</th>
<th>University of Stuttgart in Germany/ Flectofin: a hinge-less flapping mechanism inspired by nature (Fiorito et al. 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illustration</td>
<td></td>
</tr>
<tr>
<td>Movement Stimulus</td>
<td>External mechanical forces.</td>
</tr>
<tr>
<td>Movement Typology</td>
<td>Tri-dimensional change- Rotational movement.</td>
</tr>
<tr>
<td>Application / Name</td>
<td>Thematic Pavilion EXPO 2012 / SOMA /Ocean Thematic Pavilion (Fiorito et al. 2016)</td>
</tr>
<tr>
<td>Illustration</td>
<td></td>
</tr>
<tr>
<td>Movement Stimulus</td>
<td>Mechanical force.</td>
</tr>
</tbody>
</table>
4 Kinetic Shading Systems limitations and opportunities

Kinetic shading systems are coupled with intelligent systems that were introduced as solutions to adapt to the external weather conditions and to reduce energy consumptions of buildings. Based on the systems review the kinetic shading systems are able to create a more advanced integrated solution to satisfy the increasingly stricter energy performance targets, adapt to the external environmental conditions and achieve high levels of occupants’ comfort. The examples of the rotating and folding shading systems showed that they are applicable to residential buildings, commercial buildings and likely many other types of buildings. The existing applications ranged from small-scale to large-scale buildings. The existing literature shows that the use of kinetic shading systems is growing worldwide. However, applications in the UAE are only emerging, although studies showed that high amount of energy was saved when used.

Consideration of potential glare issues caused by the high reflectance of the rotating glass shading system needs to be considered. This is due to the outward tilting of the shading system where the reflections from the sun may cause glare in the building (Laustsen et al. 2008). Additionally, the rotating shading system implies a detailed design case, higher investment costs, and maintenance issues to be considered, especially if the motion mechanism is automatic (Baldinelli 2009).

The use of folding systems is still limited because actuators and sensors remain costly. Moreover, further studies should be undertaken on actuators and the focus should be on their life cycles, solar activation, and resistance to external weather conditions (Fiorito et al. 2016). Further consideration in the future is to explore environmental sensors which allow the systems to be optimized in relation to building occupancy. Since the climate of the UAE is known to have dust; more investigation needs to be done on this aspect to insure that the opening, closing and rotation motion performs properly over time.

Additionally, more studies should be done on the control and efficiency of the folding shading systems in response to various climatic conditions. Additionally, users’ behavior, perception and satisfaction with these dynamically changing shadings need to be assessed. Effective contributions would be that emerging technological improvements be developed on a wider scale with competitive cost-benefit ratios. The ideal achievement will be solutions with affordable initial cost, operationalization over long periods with minimal maintenance.
5 Conclusion

This study explored two types of kinetic shading systems; the rotating and the folding one, reviewing their function, building application and performance in general and in hot climates in particular. The outputs highlighted multiple benefits including heat gain reduction, glare control and ultimately reduced building energy use. Good opportunities of reducing the energy consumption in the extensively glazed tall mass housing in the UAE remain unexplored. Additionally, limitations of each system such as initial cost, labour cost and maintenance were discussed and remain open for improvement. This paper also stressed the need for further studies that take the impact of contextual environmental conditions such as dust and glare on the performance of these active shading systems. Further, occupants' impact, needs, perception and satisfaction need to be addressed in future research streams.

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TRANSITION IN HOUSING DESIGN AND THERMAL COMFORT IN RURAL TANZANIA

Max Eyre¹, Arman Hashemi², Heather Cruickshank³ & Maxine Jordan⁴

¹ Department of Engineering, University of Cambridge, UK, Maxeyre3@gmail.com
² School of Environment and Technology, University of Brighton, UK, A.Hashemi@brighton.ac.uk
³ Smart Villages, Cambridge, UK, heather@es4v.org
⁴ Max Fordham, London, UK, mga.jordan@gmail.com

Abstract: This study evaluates the performance of three low-income passive housing designs at providing thermal comfort for their inhabitants in temperate tropical rural Tanzania. Severe climatic conditions in these upland regions include large daily oscillations in air temperature (14°C-36°C) and high levels of solar radiation, causing overheating which affects inhabitant health and wellbeing. Inadequate shelter in these difficult climatic conditions is a widespread problem with 71% of Tanzanians living in rural areas, of which 28% of are below the national poverty line. Over the last 10 years an increasing number of houses are using modern building materials (brick or concrete walls and iron roof) rather than traditional vernacular design (mud-pole walls and thatch roof). Three designs were chosen to describe this transition. The performances of the three houses were simulated across a study year using IES and then compared against five chosen criteria to assess thermal comfort. Detailed analyses of critical times of day and specific areas of the building envelope were used to identify critical areas of design. The traditional house overheated significantly less often with smaller diurnal indoor temperature swings than the modern houses (due to its higher roof insulation and wall thermal mass). It also experienced uncomfortably low temperatures least often but maintained higher temperatures for longer during hot evenings. The modern houses outperformed the traditional house in ventilation gains with constant heat rejection throughout the day and night. The traditional house’s open structure resulted in high daytime ventilation gains and night-time heat rejection. Consideration of the position and internal gains of each room was found to be an important design factor. Across the study year the traditional design provided greater thermal comfort. However, as durability and social pressures are important factors in the choice of building materials, the design of modern materials that can mimic and improve on traditional material performance is critical to improving the health of inhabitants.

Keywords: Low Income, Housing, Passive Design, Thermal Comfort, Rural Tanzania.
1 Introduction

This research was taken to understand how building design affects thermal comfort in impoverished rural areas which are subjected to a severe climate. The focus country for the project is Tanzania, where in 2012, 71% of Tanzanians lived in rural areas. This is equivalent to just under 31 million people living in 6 million homes (Tanzania Bureau of Statistics 2012). As a high proportion of these homes are situated in regions with a temperate tropical climate this project only considers the specific case of rural temperate tropical regions in Tanzania. Only the low-income case was studied as 28% of the rural population is currently living below the national poverty line (World Bank 2014). Thus, this project aims to be applicable to a large number of homes within Tanzania, and also to other low-income regions with similar temperate tropical climates.

Thermal comfort has been identified as being particularly critical in these regions as air temperatures can exceed 35°C. This, combined with heat gains from high levels of solar radiation, as well as limited access to electricity and air conditioning facilities, can result in excessively high indoor temperatures that seriously affect the quality of life of inhabitants. Effects of thermal discomfort also include heat stroke, confusion, low sleep quality, confusion, behavioural disorders and exacerbation of health problems in susceptible groups (CIBSE 2008). Thermal discomfort can also be caused by the large daily temperature swings and colder nights found in these regions. Given the limited resources of low-income inhabitants, intelligent use of passive building design is important for provision of thermal comfort.

A 1985 report on rural Tanzanian housing concluded that “rural houses fail to satisfy biophysical and psychosocial needs of the rural inhabitants” and describes the failure of houses in protecting inhabitants from excessive heat and cold (Kalabamu 1985). This was supported by a survey of 19 mud-pole houses from the visit to a region outside Dar es Salaam. Average temperatures in this region were comparable to the study area, allowing data collected from the visit to be used to provide background information on the thermal performance of current housing. It was found that 32% of the homeowners interviewed described excessive internal temperatures as the biggest problem with their house (more than this proportion mentioned it as a problem). Six of these houses had iron roofing, all of which complained about overheating. Homeowners with thatched roofing mentioned that this was also a problem for them, but that their houses were cooler than concrete houses with iron roofs. This is supported by other studies in East Africa identifying roof construction as the key element affecting thermal comfort in low-income houses (Hashemi 2016).

Tanzanian housing has started to transition away from more traditional designs, in particular with the use of modern building materials. This project challenges the assumption that the transition is beneficial for occupants, which is largely assumed to be the case (Nguluma 2003). The decision to move away from vernacular design is often a result of factors which are not related to environmental concerns, including social aspirations, security, durability and aesthetics. However, as environmental conditions in these regions are harsh and the protection of shelter essential, they must be addressed by house design. Given that vernacular design evolves over time to adapt to local environmental conditions, it is likely to incorporate design aspects which provide thermal comfort for inhabitants. It is therefore important to assess the performance of new designs against traditional house design to ensure that the transition in house design is well informed and takes into consideration its effects on thermal comfort and health. This
analysis is also a useful tool for the identification of critical areas for good thermal comfort performance and suggestions of how this can be improved.

2 Methodology
Data for this project was collected in a literature review, site visits and surveys of three communities in rural Tanzania. It was used to define the technical aspects of housing design in temperate tropical rural Tanzania, which included house layouts, material properties and building openings. A review of the region’s climate and relevant building physics theory was undertaken. Simulations conducted in IES (VE) were then used to compare the thermal comfort performance of three house designs (selected to illustrate the transition in house design) and to identify reasons for the differences. The thermal performance of Houses 1-3 across a study year was assessed against five thermal comfort performance criteria before they were analysed over smaller timescales.

2.1 Weather Data
Tabora (Figure 1) was chosen to be the region of focus for this project due to the availability of weather data and the fact that its climate, altitude and location make it representative of Tanzanian temperate tropical upland climate. The weather data chosen for this region is given in hourly form with radiation data taken from the years 1991-2010 and temperature data from 2000-2009 to give a historically averaged weather set or Typical Meteorological Year (TMY), the source for this data was Meteonorm.

3 Housing
Literature about low-income housing design in rural regions of Tanzania with a temperate tropical upland climate (or in similar climate bands in East Africa) is relatively scarce but there are a number of papers which discuss architecture and the modernisation of the typical house (Nguluma 2003; Kalabamu 1985). This transition towards a more ‘modern’ house is an interesting one, with a transition from traditional huts towards the ‘Swahili’ house (the characteristics of which can be seen in all three houses chosen for this study) having taken place over the last century (Kalabamu 1985; Mattsson 2009; Mwakyusa 2006). This study concentrates on the more recent development of housing design, which has been largely focused on different building materials used in construction.

Housing designs chosen for analysis in this project are based on the houses described in relevant literature (Kalabamu 1985; Mattsson 2009; Mwakyusa 2006; Kalabamu 1989) and are supported by the 2002 and 2012 Tanzanian Government Housing and Population Censuses, as well as the site visit to Tanzania undertaken by a team member. A
particularly useful source has been “Traditional and contemporary building styles used in Tanzania and to develop models for current needs” by A. Mwakyusa (2006) which has an extremely comprehensive set of information on housing design across Tanzania.

The change in the main materials used for floor and roof house construction in mainland rural Tanzania between 2002 and 2012 can be seen in Figure 2. It shows that there has been a significant increase in the use of cement as a floor material, although earth is still widely used (80%) and roofing material has seen the most dramatic change, with thatch being replaced by corrugated iron.

Figure 2: Construction materials used in rural Tanzanian housing for floor (a) and roofing (b) by proportion of houses

The proportion of wall materials used in 2002 and 2012 (Figure 3) shows that mud and pole was the most commonly used wall material in 2002 but its use has fallen while baked brick use has grown. Exactly the same trends were seen in Tabora (Figure 4).

Figure 3: Construction materials used in rural Tanzanian housing for walls by proportion of houses
Figure 4: Proportion of houses with each construction material for floor, wall and roof in rural houses in Tabora in 2002 and 2012

This census data and other literature on housing design has led to the selection of three houses for further discussion and thermal performance analysis. Together they illustrate the change in house design in rural Tanzania, starting many decades ago and finishing with the most desirable ‘future’ house that is likely to become more common in rural areas when a sufficient level of economic development is achieved. All three houses follow the basic Swahili house design which, as discussed earlier, has become the dominant design across the country.

3.1 Three Study Houses (current, transition and future)

All three houses follow the same floor plan (Figure 5), are designed for 5 occupants (Tanzania Bureau of Statistics 2012) and have an indoor kitchen (Nguluma 2003). The windows are simply holes in the wall and the roof has a hipped shaped and overhangs the walls by 25cm on all sides, except for the extra shading provided on half of the front side of the house. The overlap area is completely open to air movement inside. There is no inner ceiling and there are internal walls between each room that stop at a height of 2.4m. There are no partitions between the rooms and the roof zone above this height.

Figure 5: Floor plan for all houses and photograph of House 1 design

House 1’s construction materials were most commonly used in 2002, but are still widely in use today. The walls are mud and pole (made from mud stuck onto a wooden pole
structure, see Figure 5). House 1 is the only house with different indoor and outdoor wall thicknesses (120mm and 200mm respectively). The naturally compressed sand and earth on the site before the house’s construction form the floor and the roof is made from thatched leaves.

House 2 (the transition house shown in Figure 6) describes the main changes in rural low-income housing design over the last decade. The exterior and interior walls of the house are made from baked bricks (also known as burnt bricks). The roof is made from corrugated iron and the floor is a layer of cement. The windows are larger (measuring 1m by 0.8m) and have a wooden louvre to give some occupant control over ventilation. The gap between the roof overhangs and the interior of the house is much smaller than in House 1, giving further control over air inflow.

House 3, the ‘future house’ (shown in Figure 7) is identical to House 2, except for the use of concrete blocks for all of its walls.

The key design features can be compared in Table 1 below.

<table>
<thead>
<tr>
<th>House Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Material</td>
<td>Mud &amp; pole</td>
<td>Baked bricks</td>
<td>Concrete Blocks</td>
</tr>
<tr>
<td>Roof Material</td>
<td>Thatch</td>
<td>Corrugated Iron</td>
<td>Corrugated Iron</td>
</tr>
<tr>
<td>Floor Material</td>
<td>Earth</td>
<td>Cement</td>
<td>Cement</td>
</tr>
<tr>
<td>Windows</td>
<td>Open (0.4m by 0.4m)</td>
<td>Louvre (1m by 0.8m)</td>
<td>Louvre (1m by 0.8m)</td>
</tr>
<tr>
<td>Internal Walls</td>
<td>Mud &amp; pole (up to 2.4m)</td>
<td>Baked bricks (up to 2.4m)</td>
<td>Concrete blocks (up to 2.4m)</td>
</tr>
<tr>
<td>Inner Ceiling</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Roof Shape</td>
<td>Hipped</td>
<td>Hipped</td>
<td>Hipped</td>
</tr>
</tbody>
</table>
3.2 Material Properties
The properties of the materials used in construction for Houses 1-3 can be seen in Table 2. The most representative properties for a low-income context were selected using data collected during visit, CIBSE A and the available literature on construction in Tanzania.

Table 2: Construction material properties (wall U values are external wall/internal)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thickness (mm)</th>
<th>Density (kg/m3)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>U Value (W/m²K)</th>
<th>Spec. Heat Capacity (kJ/kgK)</th>
<th>Absorptivity</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud &amp; Pole</td>
<td>200/120</td>
<td>1700</td>
<td>0.83</td>
<td>2.43/2.47</td>
<td>1</td>
<td>0.65</td>
<td>0.9</td>
</tr>
<tr>
<td>Baked Brick</td>
<td>100</td>
<td>1700</td>
<td>1</td>
<td>3.70/2.78</td>
<td>0.84</td>
<td>0.69</td>
<td>0.9</td>
</tr>
<tr>
<td>Concrete Block</td>
<td>100</td>
<td>1700</td>
<td>0.77</td>
<td>3.33/2.57</td>
<td>0.84</td>
<td>0.63</td>
<td>0.94</td>
</tr>
<tr>
<td>Roofing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thatch</td>
<td>120</td>
<td>240</td>
<td>0.07</td>
<td>0.54</td>
<td>0.18</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Corrugated Iron</td>
<td>0.7</td>
<td>7900</td>
<td>72</td>
<td>7.14</td>
<td>0.53</td>
<td>0.9</td>
<td>0.89</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>-</td>
<td>1460</td>
<td>1.28</td>
<td>2.25</td>
<td>0.88</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Cement</td>
<td>300</td>
<td>1860</td>
<td>0.72</td>
<td>1.60</td>
<td>0.84</td>
<td>0.73</td>
<td>0.93</td>
</tr>
</tbody>
</table>

4 IES (VE) Model Details
IES inputs will be discussed in this section to define the details of the model and explain the choices and assumptions made. Each room (and its associated roof area) was modelled as an individual thermal zone to allow comparisons to be made between the performances of rooms in each house, as well as between the houses. The model can be seen in Figure 8, with the three houses located in the middle of the ‘village’ used to simulate the effects of adjacent buildings.

Figure 8: ‘Village’ arrangement of houses in IES simulation

Internal gains depend on occupant behavior with 90W/person for a relatively stationary human body (CIBSE 2006). Occupancy patterns were assigned to each room based on the times of sunrise, sunset and as well as daily routine of households in rural Tanzania which was based on visit information and other sources (Raleigh International 2013; IFAD
Internal heat gains from the cooking source are also included in the model with cooking times derived from the same sources. Firewood is used for cooking fuel by 90.2% of households in rural Tanzania (Tanzania Bureau of Statistics 2012) and a peak heat output was calculated to be 1.275kW (Biomass Energy Centre 2015).

Doors are left open during the day and are shut at night (for security). The windows are left open at all times with House 1’s windows fully open and House 2 and 3’s louvre windows restricting openable area to 64.5%, according to data collected during site visits. The openings into the roof overhang are 60% open in House 1, compared to 10% in Houses 2 and 3 due to poor connections between mud walls and thatch roofing. There is no partitioning of rooms above 2.4m and there is no inner ceiling, allowing air to flow freely into and out of the common roof area.

House 1 is leaky with a high infiltration of 10ac/h as cracks and gaps are common in mud and pole walls. The better construction quality and materials of Houses 2 and 3, give these houses an infiltration of 5ac/h.

One week of internal/external temperature data was collected during the visit by a team member. This cannot be used to validate the accuracy of the model but it does give some indication of the conditions in both mud and concrete houses across a week. The same month in the simulation predicted similar results and similar differences between the two houses. The IES model will only be used to demonstrate trends and the effect of various aspects building design on thermal performance rather than giving exact results.

5 Performance Criteria

The chosen criteria for thermal comfort analysis were:

- Criterion 1: Percentage of hours above 33°C
- Criterion 2: Percentage of hours above 35°C
- Criterion 3: Percentage of hours below 18°C
- Criterion 4: TM52 Adaptive Thermal Comfort
- Criterion 5: Percentage of hours where internal dry resultant temperature > external temperature (and peak difference)

Criteria 1-3 and 5 all use indoor dry resultant temperature and percentages of hours are taken as the percentage of hours out of total hours in a year (not just for occupied hours as exact information on occupancy patterns was difficult to find and non-working family members are more likely to spend the afternoon inside). Assessment of all hours is therefore based on the perspective that a house should provide thermal comfort for all times of day.

The temperatures 33°C and 35°C used to assess overheating were derived from the CIBSE A criteria for overheating in the UK which gives maximum values of 5% and 1% for temperatures of 25°C and 28°C respectively (CIBSE 2006) which are clearly unsuitable for Tanzania’s hot climate and the low-income context of this study. A simple comparison of the percentage of hours exceeding these temperatures in London was used to select the two equivalent temperatures for Tabora.

The sensation of temperature and its effect on health are dependent on the acclimatisation of a person to their environment. Adaptive thermal comfort model CIBSE TM52 was selected to take this into consideration and assesses performance against three criteria, giving a classification of overheating if a room fails any two of the three criteria. A summary
of the key details of the TM52 method will be given here but a more detailed explanation of the method can be found in IES’s TM52 explanation (IES 2013).

The three criteria are:

- Hours of exceedence: “The number of hours during which $\Delta T$ is greater than or equal to one degree (°K) shall not be more than 3% of occupied hours. $\Delta T$ is defined as operative temperature [dry resultant temperature] less the maximum acceptable temperature.”
- Maximum daily weighted overheating exceedence: Assesses the severity of overheating across a day in terms of both duration and magnitude of temperature (its units are degree hours). It is weighted to account for both of these terms, with a value greater than 6°C/hr resulting in failure in this criterion.
- Upper limit on temperature: Sets an absolute maximum value for indoor operative temperature where the maximum $\Delta T$ is set to 4°C.

The maximum acceptable temperature is the upper limit of the thermal comfort threshold and is calculated from:

$$T_{max} = 0.33T_{rm} + 18.8 + S.A.R$$

where $T_{rm}$ is the exponentially weighted running mean of the daily mean outdoor air temperature, and the suggested acceptable range (S.A.R) is 4°C (the maximum range suggested by CIBSE as performance expectations are lower for the context of this study).

6 Results and Discussion

6.1 Comparison of Houses

6.1.1 Criteria 1 and 2

Figure 9 and Figure 10 show the performance of each room of Houses 1-3 in Criteria 1 and 2 with House 1 outperforming the other houses. It maintains indoor temperatures below 35°C in all rooms for the entire study year and only exceeds 33°C in less than 0.5% of hours. The highest proportion of overheating occurred in the kitchen (0.5%) while Houses 2 and 3 experienced overheating for 6-7% hours in all rooms except for the hallway/bedroom (3.5%). All rooms in House 1 stayed below the maximum of 1% and 5% hours/year in Criteria 1 and 2 but only the hallway/bedroom passed these criteria in Houses 2 and 3. This shows that a significant proportion of the year will be extremely uncomfortable for inhabitants. The results for Houses 2 and 3 were very similar for each room, with House 3 performing marginally better.
6.1.2 Criterion 3
House 1 outperformed the other two houses across all rooms (see Figure 11). The hallway/bedroom had the highest proportion of hours spent below 18°C in all three houses, and the kitchen in all three houses had the lowest proportion of hours of thermal discomfort. Again, House 3 marginally outperformed House 2 in all of the rooms.
6.1.3 Criterion 4

TM52 Criteria I (Figure 12) follows the same trend of House 1 outperforming the other houses with all rooms in it spending less than 0.5% of the year with temperatures 1°C or greater than the calculated real time maximum adaptive temperature. Houses 2 and 3 exceed the maximum allowable proportion of the year (3%), with the kitchen and bedrooms 1 and 2 exceeding it considerably (7-8%). Therefore all rooms in House 1 pass TM52 Criteria I, while Houses 2 and 3 fail this criteria in every room. The highest proportion of overheating occurred in the kitchen and bedroom 1, less in bedroom 2 and significantly less in the hallway/bedroom.

![Figure 12: Criterion 4: TM52 Criteria I Percentage of hours in study year for which room temperature is over 1°C higher than maximum adaptive temperature](image)

The results for TM52 Criteria II (Table 3) confirm that providing thermal comfort in terms of both temperature and duration of overheating is a difficult challenge with all three houses all failing. House 1 results follow the same trends that have been seen in all of the previous criteria: far outperforming the other two houses (although it still exceeds the maximum value by over 300%) with the kitchen subjected to the highest level of overheating. Again the results for Houses 2 and 3 are close in value and show that the lowest level of exceedance occurs in the hallway/bedroom.

<table>
<thead>
<tr>
<th>House Number</th>
<th>Kitchen</th>
<th>Hallway/Bedroom</th>
<th>Bedroom 1</th>
<th>Bedroom 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM52 Criteria II Daily weighted exceedence (°C hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>28</td>
<td>25</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>48</td>
<td>62</td>
<td>69</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>47</td>
<td>61</td>
<td>69</td>
</tr>
<tr>
<td>TM52 Criteria III Max. ΔT (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>7</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

For TM52 Criteria III (Table 3) the highest values of ΔT are shown, with all rooms in House 1 passing criteria and all rooms in Houses 2 and 3 failing. In both of these houses bedroom 1 exhibits the highest peak ΔT with a value of 10°C.
Overall, all rooms in Houses 2 and 3 failed Criterion 4 because they failed TM52 Criteria I, II and III. All of the rooms in House 1 passed TM52 Criteria I and III and therefore passed Criterion 4.

6.1.4 Criterion 5

In House 1 indoor temperatures of all rooms were greater than the outside temperature for 60% of the year, apart from the kitchen which was 67%. Houses 2 and 3 performed badly in all rooms (hallway/bedroom 84%, kitchen 93% and bedroom 2 97%). These proportions are extremely high and would suggest a high level of thermal discomfort.

6.2 Performance Over Time

The variation of room temperature with time follows a similar diurnal cycle throughout the year for all cases (limited seasonal change). Figure 13 plots the temperatures of bedroom 1 (representative of all rooms) in all three houses over a hot five-day period. The large swings in ambient temperature are mimicked by the indoor room temperatures, with Houses 2 and 3 exhibiting almost identical results.

Overheating in Houses 2 and 3 is again confirmed to be significantly worse than in House 1 with the temperature above the outdoor temperature for the duration of this sample period. Daily temperature swings in Houses 2 and 3 are often greater than the diurnal outdoor variation, while House 1 can be seen to have reduced these swings significantly with lower daytime temperatures and higher night-time temperatures.

A ‘typical warm day’ was used to analyse performance across a day. Results for bedroom 1 (Figure 14) show temperature moderation in House 1 and a small time lag between external and internal temperature rise. The performance of the kitchen in each house (Figure 15) presents a different curve shape to that seen for the other rooms with three small peaks which are due to the high internal cooking gains in the morning, afternoon and evening.
The changes in room temperature for all rooms in Houses 1-3 on this day can be seen in snapshots at four hourly intervals (and at 3am) in Figure 16. The temperatures for each room are denoted by colour with reference to the key. Figures 16(a-d) show that Houses 2 and 3 heat up faster than House 1, with a temperature difference of ~2°C. At 10pm (Figure 16(e)) this temperature difference becomes negligible as all rooms in each house fall to 24°C. The outdoor temperature is 22°C and there are no external gains. The temperatures in all houses continue falling (Figure 16(f)) and by 3am Houses 2 and 3 are cooler than House 1. The heating and cooling rates in House 1 are therefore lower than in House 2 and 3. House 1 is slower to overheat during the day (reducing daytime thermal discomfort) but on hotter nights House 1 will maintain higher temperatures than the other two houses. This may result in thermal discomfort during the earlier part of the night, at a point when occupants will be sleeping indoors.
6.3 Summary of Observations

1. Across the entire year House 1 overheats and experiences uncomfortably low temperatures significantly less often than Houses 2 and 3. On a daily basis it is subjected to lower diurnal temperature swings with lower daytime temperatures and marginally higher night-time temperatures when compared to outdoor temperatures and Houses 2 and 3.

2. Overheating in House 1 occurs most often in the kitchen and the least often in bedroom 2.

3. Across the year House 3 both overheats and experiences uncomfortably low temperatures marginally less often than House 2.

4. Overheating in Houses 2 and 3 occurs most often in the kitchen and bedroom 1.

5. Overheating in Houses 2 and 3 occurs the least in the hallway/bedroom but the daily weighted exceedence is highest in bedroom 2.

6.4 Analysis of Key Areas

Observations 1-5 will be explained by further analysis of the house performances in the followings sections.
6.4.1 Roof

Conduction gain through the roof for the ‘typical warm day’ (Figure 17) shows that daytime conduction gains through House 2 and 3’s roofs are far higher than House 1. The conduction gain increases from sunrise until it reaches a very high peak value of 2kW when the sun is directly overhead before decreasing over the afternoon. In contrast, House 1 maintains a steady level of conduction gain throughout the day with a peak value of just 0.1kW between midday and 2pm. At night-time House 2 and 3’s roof conduction negative gains indicate heat emission from the house. Corrugated iron and thatch have very low thermal storage capability and therefore conduction gains are due to direct conduction only. The high U-value of House 2 and 3’s corrugated iron (7.14W/m²K) allows a much higher heat flux through the roof than House 1’s thatched roofing (U-value of just 0.54W/m²K). This results in higher heat transmission into the house when external temperatures and solar radiation are high and a high transmission of heat out of the house when internal temperatures are higher than external temperatures.

These results explain the behaviour described in Observation 1, with iron roofing a key contributor to daytime overheating. The limited levels of heat transfer permitted by House 1’s thatch roof keep internal temperatures low during the daytime and prevent internally stored heat from being released at night, resulting in higher night-time temperatures.

6.4.2 Walls

The conduction gain through external walls is plotted for the hallway/bedroom on the ‘typical warm day’ (Figure 18), showing that the conduction gain does not always vary directly with outdoor temperature. This is because, unlike the roof materials, the wall materials have considerable thermal storage capacity, resulting in heat energy being stored in the material during the hottest periods of the day and then released at a later time. The thick mud and pole walls in House 1 provide the greatest thermal storage capacity and the largest time lag for emission of heat energy (see ρCλ values in Table 4). This can be seen in Figure 18, with the walls emitting heat energy (positive conduction gain) during the night-time when ambient temperatures are lowest, and absorbing heat energy (negative conduction gain) during the hottest part of the day. This timing is good for moderating internal temperatures and is a key factor in explaining the behaviour described in Observation 1. However, the time lag is not perfect, as the walls start to emit...
heat energy from 6pm onwards (when ambient temperatures are still relatively high at 26°C). This explains House 1’s higher temperatures during the early evening.

![Figure 18: Wall conduction gains](image)

**Table 4: Values for wall material thermal storage capacity term ρCλ for Houses 1-3**

<table>
<thead>
<tr>
<th>Material</th>
<th>House 1</th>
<th>House 2</th>
<th>House 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud and Pole</td>
<td>1411</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baked Bricks</td>
<td>1428</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete Blocks</td>
<td>1100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The thermal storage of the baked brick and concrete walls of House 2 and 3 is considerably less effective at internal temperature regulation as their walls absorb heat during the night-time/early morning (when temperatures are lowest) and emit/conduct heat energy into the house from midday until 6am the next morning. This heat flux into the room occurs during the hottest period of the day and increases overheating in these two houses. The U-values of these external walls (see Table 2) are higher than mud-pole walls, resulting in a faster heat wave reaching the inside surface faster. This is an important factor for Observation 1.

Figure 18 shows that the performance of House 3’s concrete walls is slightly closer to that of the mud-pole walls with higher heat emittance than House 2’s baked bricks in the cooler night-time/early morning period and lower heat emittance (and conductance into the house) in the hotter period of the day. This is due to concrete having lower U-value than baked bricks (slower waves delay heat gains making House 3’s graph the same as House 2’s but shifted to the right). This slightly improved thermal moderation behaviour is a contributing factor for Observation 3 which states that House 3 has more moderate temperature swings than House 2.
6.4.3 External Ventilation and Infiltration

House 1’s large roof overhang openings and gaps and cracks give it greater infiltration and external ventilation than Houses 2 and 3. Its higher airflow increases gains (peak value 1.2kW) during the daytime and negative gains (heat removal) during the night-time (Figure 19). The benefits of high ventilation during hot nights is clear, with House 1 showing a peak heat rejection of 1.2kW at 4am for this day. This will also be good for removal of heat stored in the mud walls. However, during the daytime this ventilation will contribute significantly to rises in indoor temperature.

Figure 19: External ventilation and infiltration gain

Houses 2 and 3 exhibit similar results because they have the same openings and level of workmanship. Their ventilation gains are negative throughout the entire day and reach a peak heat rejection level of 0.9kW during the hottest period of the day. The constant rejection of heat by ventilation in these two houses is beneficial for thermal comfort during hot days.

Houses 2 and 3 clearly outperform House 1 in terms of the contribution of ventilation towards preventing overheating, although this is not immediately apparent from the assessment of overheating in this project. However, on closer inspection of the results for Criteria 2-4 it can be seen that the hallway/bedroom in House 1 is the room that spends the second highest proportion of time overheating. This can be attributed to the fact that it is the room with the largest amount of external openings for cross-ventilation. The hallway/bedroom is the most ventilated room in Houses 2 and 3 and is therefore the coolest room (as they only have negative gains) as was stated in Observation 5. This analysis has shown the impact that controlling ventilation can have on heat gain/rejection for the houses.

6.4.4 Solar Gain

Table 5 shows the maximum gains, when they occur and the mean values for each room in Houses 1 and 2. The sun path for Tabora (computed in IES-VE) showed that the angle of the sun varies throughout the year affecting the solar gain at two periods of the year. North-facing rooms (bedroom 2 and kitchen) receive highest solar gains in June and the
southern-facing rooms (bedroom 1 and hallway/bedroom) do so in December. The lower gains in House 1 are due to its smaller windows.

Table 5: Internal solar gains for Houses 1 and 2 across study year

<table>
<thead>
<tr>
<th>Location</th>
<th>Peak Value (W)</th>
<th>Time of Peak</th>
<th>Mean (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>House 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>67.3</td>
<td>12:30, 23/Jun</td>
<td>9.6</td>
</tr>
<tr>
<td>Hallway/Bedroom</td>
<td>32.7</td>
<td>08:30, 03/Jan</td>
<td>5.7</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>45.4</td>
<td>14:30, 24/Dec</td>
<td>7.3</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>67.4</td>
<td>12:30, 23/Jun</td>
<td>9.6</td>
</tr>
<tr>
<td>House 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>136.3</td>
<td>12:30, 23/Jun</td>
<td>20.4</td>
</tr>
<tr>
<td>Hallway/Bedroom</td>
<td>62.8</td>
<td>08:30, 03/Jan</td>
<td>11.8</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>84.8</td>
<td>16:30, 20/Dec</td>
<td>15.4</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>136.2</td>
<td>12:30, 23/Jun</td>
<td>20.5</td>
</tr>
</tbody>
</table>

Radiation flux reaches a maximum value of 1.3kW/m² during the year. There will be relatively high absorption of this by all of the houses as the walls have absorptivities of 0.63-0.69. The corrugated iron roofs will absorb a particularly high level of this radiation in comparison with the thatched roofing due to its absorptivity of 0.9 (thatch has 0.6). There will be periods of very high external solar gain during the year, with House 1 absorbing the least through the roof. Houses 2 and 3 absorb significantly more due to the higher roof absorptivity, and House 3 will absorb marginally less radiative energy through its walls than House 2 because of its lower absorptivity (0.63 compared to 0.69). These key points explain Observations 1 and 3. This is because high radiation gains (combined with low insulation) result in more overheating in Houses 2 and 3 when compared to House 1.

The orientation of long walls and windows facing in the north-south direction which was chosen for the simulation was compared with an east-west orientation (rotation by 90 degrees). It found that the mean solar gain in every room in Houses 1-3 was around 30% lower for the north-south orientation because of the position of the sun. For overheating prevention maximum values of solar gain are more important as days of high solar radiation are the most likely to heat up the houses. It was found that the annual peak value of solar radiation was 50% less for the north-south orientation. The direct east-west movement of the sun affects bedroom 2 for Houses 2 and 3 because, as an east-facing room, it is the first to heat up in the morning and then has its high indoor temperature sustained throughout the day by high ambient temperatures. As a result it spends the longest time at high temperatures of all the rooms, which results in a high daily weighted exceedence.

The afternoon solar radiation falls more on the western side of the house, increasing the solar gains in the kitchen and bedroom 1 at the time of highest ambient temperature, resulting in these rooms overheating more often than others (Observation 4). Although the kitchen was the most susceptible room to overheating in House 1 (Observation 2), this is not entirely due to solar gain because it is less susceptible to conduction gains (due to its
lower roof absorptivity and higher levels of insulation and thermal mass). Instead the higher occurrence of overheating in this room (and not bedroom 1) is due to the combined contributions of internal gains and external gains, because internal gains have more of an impact on overheating when external gains are lower. This is also the reason why cooking gains (occupancy gains have minimal effect) have more of an effect on House 1 than the other two houses.

7 Conclusions

The study has shown that the ‘current house’ (House 1) offers a far greater level of thermal comfort than the ‘transition house’ (House 2) and the ‘future house’ (House 3) for the temperate tropical climate of Tanzania. This was shown by its vastly superior performance across all criteria. It does this by moderating diurnal temperatures, therefore reducing the incidence of overheating during the daytime and cold temperatures at night-time. This was found to be due to the thermal mass of the thick mud-poles walls and insulation and lower solar radiation absorption through the thatch roof. The iron roofing in Houses 2 and 3 was found to perform particularly badly due to its very high conduction gains. However, House 1 did not perform the best in all cases, with its more open structure resulting in higher daytime ventilation gains than the other two houses. The fact that it cools down more slowly than Houses 2 and 3 each night also means it can be more uncomfortable during hotter evenings. The study also found that House 3 performs marginally better than House 2 because of its slightly lower wall conduction gains and internal solar gains. Overall, it must be concluded that the thermal comfort provided by all three houses is not acceptable and can be improved through further analysis of several critical design areas which were identified in the study. These include reducing gains through the roof, controlling ventilation at different times of day and designing thermal mass for optimal time lag and temperature moderation.

The rooms in the houses also had varying levels of thermal comfort, in particular with the kitchen and bedroom 1 on the western side suffering from afternoon solar gains combined with high ambient temperatures. The internal gains from the kitchen in House 1 were also more dominant in dictating thermal comfort in the house. The results show that building design should also take into consideration the position and use of each room, and design them accordingly (using additional thermal mass, ventilation or shading) to reduce the effects of the most dominant gains on thermal comfort for each case.

The results from this study highlight a serious deficiency in appropriate design of modern low-income housing for thermal comfort in the temperate tropical Tanzanian climate. Although traditional housing design may be viewed as no longer being suitable by some people because of non-thermal factors (e.g. durability, security and disease vectors), the key design principles which make them effective at providing thermal comfort should be considered and applied to improving modern house designs.

Acknowledgements

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OPEN STREET MAP, www.openstreetmap.org


ENERGY EFFICIENCY VS. INDOOR AIR QUALITY: A REVIEW OF OPTIMAL RETROFIT OF EXISTING BUILDINGS

Enas Alkhateeb¹ & Hasim Altan²

¹ Sustainable Design of the Built Environment, Faculty of Engineering & IT, British University in Dubai, UAE, enasassami@gmail.com
² Department of Architectural Engineering, College of Engineering, University of Sharjah, Sharjah, UAE, hasimaltan@gmail.com

Abstract: Countries worldwide strive to mitigate the buildings’ impact on the environment by reducing energy demand. Since the majority of buildings already exist, retrofitting these buildings with energy efficiency measures provides a greatest chance to meet our carbon emission obligations. The United Arab Emirates (UAE) is among the few countries in the Middle East that started focusing on retrofitting their buildings. However, Indoor Air Quality (IAQ) is still neglected and any energy declaration without considering IAQ is illogical. Many recent health reports stated that green building residents’ future might witness health degradation. The greener the building, the greater the occupants’ chance to develop symptoms of asthma, airborne respiratory infection, lung cancer and radio vascular disease. These cases are more noticeable in extreme climate regions with limited access to natural ventilation. In order to obtain a healthy productive society, it is essential to follow a balanced approach that considers both issues; saving energy and creating healthy indoor environments. This paper provides an analytical review of the negative impact of energy efficiency retrofit measures on human health and productivity. In addition, it will highlight the necessary actions to reach the optimal status in terms of energy efficient retrofit building that considers IAQ with the same importance as saving energy or in general reducing end-user energy demand. The result reveals the importance of considering a holistic approach in retrofitting buildings that will consider all systems, as well as to provide an efficient mechanical ventilation with heat recovery (MVHR) system that maintains 0.5 air changes per hour (ac/h) as a minimal level.

Keywords: Existing Buildings, Optimal Retrofit, Energy Efficiency, Indoor Air Quality, Mechanical Ventilation
1 Introduction
The countries worldwide strive to mitigate the buildings’ impact on the environment through managing energy demand. According to Phoenix (2015), since the majority of buildings already exist, improving their energy efficiency provides the greatest chance for a sustainable future. However, it is stated "an energy declaration without a declaration related to the indoor environment, makes no sense” Olesen et al (2006).

Most people spend around 90% of their lives inside buildings. The nature of the enclosed environment affects the occupants’ lifestyle, health and level of productivity. It was found that the energy efficient buildings that may cause reduction in productivity or an increment in sick leaves by even a small percentage as 1% can cause more cost compared to the savings from the implemented energy retrofit measures (Tom 2008). For that, energy efficient buildings need to meet the intended function of the building and should improve the occupants’ health, comfort and productivity (Persily & Emmerich, 2012). As a result, many researches emphasize on the importance of considering the Indoor Environment Quality (IEQ) issue within the energy efficiency retrofit programs, especially the Indoor Air Quality (IAQ), which expands the opportunity to obtain great improvements in all aspects (Noris et al. 2013).

According to Fisk et al. (2014), the opportunity to save energy and improve IEQ through retrofitting buildings is tangible; however, in recent times, IEQ does not grasp as much attention as energy savings. A review conducted on a 19 energy retrofit analysis toolkits for commercial buildings (Lee et al. 2015). They found that only 25% of these tools mentioned IEQ. It is essential to balance between the implemented energy efficiency measures and the IEQ, since some measures can degrade IEQ, which will affect health and productivity. It is found that people who live in energy efficient social houses in the UK have higher chances of reporting that they had seen the doctor for asthma symptoms in the last 12 months (Fisk et al. 2015).

This paper aims to define the optimal balance in implementing energy efficiency retrofit measures without compromising thermal comfort, as well as indoor air quality. It is very important to review the related risks and efforts in such an area, in order to provide a broader image that will help achieve a healthy energy efficient building stock.

2 Methodology
Extensive literature review has been conducted as part of this study. The main targets were peer-reviewed journals, articles, governmental and official reports that tackle IEQ in general. However, more focus deployed on energy efficient retrofitted buildings (EERBs), and the impact of high performance of EERBs on health and productivity were highlighted. The retrofit measures have also been categorized based on their impact on some IEQ parameters (i.e. thermal condition and air quality). A balanced approach between providing EERBs and IEQ was highlighted.

3 Indoor Environment Quality (IEQ)
Retrofitting existing buildings has been reinforced in the last two decades for its substantial impact in reducing the CO₂ emission (Liu & Guo 2013). However, the nature of the enclosed environment affects the occupants’ lifestyle, health and level of productivity. Any physical degradation in the building systems affect the health and the performance of occupants. It was stated that the energy efficient buildings that may cause a reduction in productivity or an increment of sick leaves, even by a small percentage such as 1%, can cause more cost compared to the savings from the implemented energy retrofit measures
(Tom, 2008). For that, energy efficient buildings need to meet the intended function of the building and should improve the occupants' health, comfort and productivity.

As a result, many research emphasized the importance of considering the indoor environment quality (IEQ) issue within the energy efficiency retrofit programs, especially the indoor air quality (IAQ), which expands the opportunity to obtain great improvements in all aspects (Noris et al. 2013). However, in some cases, if the upgrade is not performed properly, it might negatively affect the indoor air quality (EPA 2016).

7.1 Thermal Comfort (TC)
Thermal comfort has a great impact on occupants’ performance and the level of productivity. There are six factors that may affect thermal comfort: dry bulb temperature, air speed, radiant temperature, humidity, metabolic rate and clothing insulation. However, the occupants’ perception and preferences defines the thermal comfort, and since this matter is subjective, satisfying 80% of the occupants’ needs is considered a positive sign for an appropriate thermal environment. However, it was found that people who are equipped with training on the features of energy efficient buildings are more likely to be thermally pleased with their indoor environment (Day & Gunderson 2015).

7.2 Indoor Air Quality (IAQ)
The IAQ's impact on occupant health and comfort can be linked directly to the levels of the indoor contaminates and the thermal comfort parameters (Persily & Emmerich 2012). The main cause for indoor air pollution in buildings is pollutants and sources of pollutants that release particles or gases into the air. They can be summarized in to five categories: combustion sources, building materials (deteriorated asbestos, newly installed flooring, cabinetry), household items, outdoor sources (e.g. radon, pesticides) and biological pollutants (EPA 2016 & NIOSH 2015).

High temperature and relative humidity can raise the concentration of some contaminants; moreover, with the lack of adequate ventilation, the air quality gets worse. To obtain a healthy indoor air quality, it is essential to minimize the rate of indoor emission for all contaminants. In addition, it is crucial to provide sufficient ventilation, in addition to the use of air filtration (Nazaroff 2013 & Shrubsole et al. 2012).

4 Retrofit Measures and their Impact on IEQ (TC & IAQ)
Energy efficiency measures focus mainly on reducing the buildings’ energy demands for heating or cooling purposes. These measures could be passive, active or behavioral ones (Ma et al. 2012). Energy efficiency retrofit measures show either positive, negative or neutral impact on the IEQ. In most cases, retrofit strategies are found to affect the TC positively (Itani et al. 2013 Kwong et al. 2014 & Engelmann et al. 2013). On the other hand, air sealing the buildings will minimize the rate of exchanging air, which leads to more concentration of air pollutants; hence, a decreased level of productivity and the presence of sick buildings are more likely (Hong et al. 2015). Noris et al. (2013) summarize some of the energy retrofit measures and their impact on IEQ in general as shown in Table 1.
Table 3: Expected retrofit’s impacts on energy and IEQ (TC & IAQ) (Noris et al. 2013)

<table>
<thead>
<tr>
<th>Retrofit Measure</th>
<th>Energy Impacts</th>
<th>IEQ Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope Air Sealing</td>
<td>Heating and cooling load reduction</td>
<td>Reduces pollutant entry from outside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduces outdoor air ventilation which affect negatively IAQ</td>
</tr>
<tr>
<td>Add Insulation</td>
<td>Heating and cooling load reduction</td>
<td>Improves thermal comfort and noise transmission</td>
</tr>
<tr>
<td>Change the HVAC ductwork seal return plenum</td>
<td>Heating and cooling load reduction</td>
<td>Reduces pollutants from other nearby apartments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May improve thermal comfort</td>
</tr>
<tr>
<td>Double pane glazing</td>
<td>Heating and cooling load reduction</td>
<td>Reduces radiant heat losses and improve comfort</td>
</tr>
<tr>
<td>Solar water heater</td>
<td>Reduction in energy</td>
<td>Reduces risk of combustion pollutant spillage to indoors</td>
</tr>
<tr>
<td>Provide personal comfort system (PCS) such as ceiling and desk fans</td>
<td>Cooling demand reduction</td>
<td>Thermal comfort improvement</td>
</tr>
<tr>
<td>Installing high-efficiency particular air (HEPA) filter</td>
<td>consuming more electricity</td>
<td>Minimize the level of indoor particles</td>
</tr>
</tbody>
</table>

There is an opposite relation between building sealing and the IAQ. Many studies were applied to investigate this issue and its consequences. For example, Sharp et al. (2015) conduct a recent study, which aims to evaluate the performance of social houses that are considered energy efficient buildings. "Standard Assessment Procedure (SAP) rating" was applied. The result shows that the more SAP rating increases by unit, the chances of getting asthma increases by 2%.

**Energy Efficiency Retrofits and IAQ**

Retrofitting buildings is among the promising field to achieve tangible results on reducing the emission of CO2. Due to this, many projects pop-out with different energy saving schemes having the same goal of providing zero or nearly zero carbon buildings. "FutureFit" is a retrofitting program in England carried by Affinity Sutton LTD. A study was held to assess the impact of retrofit on occupants’ health. The study points-out the problem of condensation that appears to increase after retrofit work, which was the main complaint by occupants, followed by the ventilation and mould growth (Affinity Sutton 2013).

Another study was performed by the National House Building Council (NHBC) tested the air permeability in 23 sampled houses. They found out that these houses lack the adequate ventilation, which would result in pollutants to build-up, increasing the risk of having asthma and cute respiratory conditions (NHBC 2011). Buildings with air-tightness below 10 m3/(hm2) are recommended to apply a mechanical ventilation, whilst BRE believes that in order to avoid the moisture build-up, a minimum rate of air exchange should be 0.5 ac/h, which is corresponded to an air leakage of 10 m3/(hm2) (Awbi 2016). Moreover, a study was conducted by the Building Research Establishment (BRE) on 37 retrofitted homes in England; they followed measurement methods, in addition to collected data from questionnaires. The relation between the concentration of some main indoor contaminants and the rate of ventilation was found (Awbi 2016).

All the above studies show the strong evidence of the impact of low ventilation rate in buildings on the IAQ degradation, which is expected to be more aggressive with future projects, which may cause serious health issues. Moreover, Persily & Emmerich, (2012),
list few retrofit actions that could affect the IAQ in a negative way in both commercial and institutional buildings (See Table 2).

<table>
<thead>
<tr>
<th>Energy Efficiency Strategy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced outdoor air ventilation rates</td>
<td>Increases concentrations of contaminants with indoor sources</td>
</tr>
<tr>
<td>Increased thermal insulation</td>
<td>if are not well designed, can increase the possibility of condensation in building envelopes (which increase the potential of biological growth)</td>
</tr>
<tr>
<td>Cooling equipment efficiency increases</td>
<td>If system design, control and operation do not adequately address latent loads may increase indoor humidity levels (causing potential biological growth)</td>
</tr>
</tbody>
</table>

A survey conducted by Awbi (2015) was to investigate the impact of energy efficient retrofit measures and air tightness on pollution levels and health. It is concluded that if there is no additional IAQ consideration and intervention provided to enhance the ventilation rate in buildings, an expected 80% increase in asthma, increase in TVOC concentration up to 60% above the WHO 24h limits, and increase in the concentration of NO₂ up to 30% above WHO annual limits by 2050.

To capture a broader picture of the impact of retrofit on IEQ, different types of buildings have been chosen to be reviewed (See Table 3). The used retrofit measures have been highlighted as well as their impacts on energy consumption and the IEQ (TC & IAQ). Many retrofitted cases in different climate regions show a positive impact of some measures on thermal comfort. For example, implementing active easy measures with zero initial cost, such as raising the cooling temperature set-point or reducing the heating set-point around 1-2°C, may provide a tangible reduction in cooling and heating demand without compromising the thermal comfort (Itani et al. 2013, Kwong et al. 2014 & Du et al. 2015). Moreover, integrating some passive measures, such as insulating external walls with low heating temperature, can increase the impact of retrofit on energy savings without compromising thermal comfort (Wang et al. 2015).

Eventually, a full scale building retrofit’s that consider passive and active measures shows reduction in energy up to 50% and the indoor environment shows a good improvement as well (Chen et al. 2015). Although a couple of cases show thermal discomfort, (Gangisetti et al. 2016 & Chen et al. 2015), the reasons behind this discomfort was easy to contain in the first case, whilst in the latter one; other reasons were found to be behind the discomfort rather that the retrofit measures implementation. On the contrary, regarding air quality, the majority of cases show a negative impact on the provided air quality. The complains regarding air quality disappear with the provision of mechanical ventilation (MV), (Noris et al. 2013 & Peretti et al. 2015) or with the increment of the ventilation rates VR, which both demand more energy (Fisk 2012).
### Table 5: Impact of energy efficient retrofit measures on IEQ (TC & IAQ)

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Building Type</th>
<th>Location</th>
<th>Retrofit Measures</th>
<th>Retrofit Impact</th>
</tr>
</thead>
</table>
| Fisk 2012                 | Office Building     | USA               | - increase VRs to 10 L/s/person  
- increase VRs to 15 L/s/person  
Add economizer               | Increased Energy saving  
*Performance increased  
*Decreased in SBS symptoms  
*Less absence days All *    |
| Peretti et al. 2015       | Social Houses       | Italy             | 1) - Increased thermal insulation *  
- Efficient radiant ceiling sys. instead of gas heater *  
2) - (*) + Mechanical ventilation | Not evaluated  
No change in thermal comfort between 1&2 (Occupants' behavior impact)  
Air quality is higher in (2) |
| Chen et al. 2015          | Residential         | North China       | 1) Envelope (walls, roof, windows)  
2) space heating metering system & temp. control of space heating system. | Nearly 65% savings in energy  
66.7% of occupants were satisfied  
16.6% feel hot  
16.6% feel cold  
In general, great improvement |
| Martuzevicius et al. 2013 | Multi-family apartment building | Northern Europe *Finland & #Lithuania | Thermal Insulation upgrade  
HVAC systems upgrade | Not evaluated  
*35% not satisfied with IAQ  
Asthma & respiratory 5.3%  
# 35.3% not satisfied with IAQ  
Asthma & respiratory 0% |
| Noris et al. 2013         | Low-income residents Apartment s | U.S.A. | Envelope sealing, Attic insulation, (MV) Mechanical ventilation, HVAC replacement, provide air particle cleaner | Energy savings  
General improvement in air quality  
IEQ parameters other than particles improved more with MV |
| Andersen et al. 2015      | Residential         | U.S.A.            | Comprehensive energy retrofit (not specified) | Not evaluated  
Recommended Temperature and RH for healthy environment were detected during heating season, not cooling season. |
| Gangisetti et al. 2016    | Office              | U.S.A.            | Variable air Volume (VAV) minimal flow | Significant Energy Savings  
Little concern with thermal discomfort |
| Ascione et al. 2015       | Educationa l Buildings | South of Italy    | - Green roof as a retrofit element on already refurbished building  
- Hybrid approach | 2%-3.4% energy savings in summer  
18% energy savings  
-Thermal comfort are always fulfilled even with HVAC turned off  
-Mean value of the comfort adaptive range |
| Itani et al. 2011         | Office Building     | Lebanon           | - raising indoor cooling set-point  
- lighting control  
- Night pre-cooling  
- improve COP | -3.4% savings  
-2.6%  
-0.9%  
-2.1%  
Thermal comfort was not compromised |
| Wang et al. 2015          | Multi-family building | Sweden            | Low temperature Heating LTH with five different passive retrofit | 55.3% savings on total energy  
52.8% on primary energy  
Thermal performance was improved |
The question that puzzles the interested advocators is: “is providing energy efficiency strategies and good air quality hard to be achieved in a building?” The first perception to the relation between energy and IAQ leads to believe that those two goals are conflicting. However, the topic is more complex and indeed, there are many strategies and considerations that can improve both aspects.

5 Energy Efficient Buildings and IEQ

Although some studies recommend applying air-tightness standards, such as Passive House Standards on the existing stock (Logue et al. 2013), the impact of such approach on health started grabbing considerable attention. A study was conducted by Howieson et al. (2013) to assess the performance of a recent completed “Passive House” and the air tightness impact on the indoor pollutant concentration. The results from a real life situation where the air tightness is 5 m³/m²/h @ 50 Pa and a trickle ventilation is the only provided strategy in the sleeping zones; the CO₂ levels shows a poor IAQ environment. A significantly greater rate of ventilation is required. It was found that just relying on trickle ventilators does not meet the recommended standards. They concluded that the recommended ventilation according to any building regulation should be based on a house model that views occupied rooms as disconnected volume to avoid the impact of trickle ventilation (Howieson et al. 2013).

Moreover, a low energy performance building was chosen as a case study to evaluate the IEQ level. The chosen building goes under class A+ (less than 25 kWh/m² year). Through monitoring data during summer and winter periods, the result shows low IEQ particularly in summer time (Fabbri & Tronchin 2015).

To keep it simple, for more airtight, ventilate right. However, Howieson et al. (2013) stated that the ventilation system should be able to provide the following in order to obtain a healthy environment:
- An adequate out air supply to support the human respiratory needs of IAQ.
- Remove any health hazardous elements such as air pollutants especially from areas that have high cementation levels.
- Reduce the chance of mould growth or harmful bacteria by removing the excess water vapor where it is formed in ample quantities.
- Improving energy efficiency by reducing ventilation rate without providing any effective ventilation system is more likely to provide a hazardous and toxic indoor environment. This impact will affect the occupants’ health in the long-term.

6 Ventilation vs. Infiltration

Persily and Emmerich (2012) explain the importance of differentiating between infiltration and ventilation. Although infiltration is bad for both energy consumption and IAQ, ventilation (natural and mechanical) is a key element in providing a healthy IAQ. A study on the U.S. residential stock conducted by Logue et al. (2013) shows that by controlling air infiltration through effective envelope sealing as a solo retrofit measure, it could save around $22 billion annually. This retrofit study was conducted along with the provision of mechanical ventilation when needed according to ASHRAE standards 62.2 (Logue et al. 2013). According to the study, the energy demand due to mechanical ventilation could be increased by 0.07 quads.

However, the relation between IAQ and energy efficiency goes beyond the rate of ventilation. The holistic approach to achieve energy efficiency and healthy IAQ level is the needed solution. Table 4 presents some of the strategies that can be beneficial for both IAQ and energy efficiency. Although there are few strategies that could improve the air
quality and does not affect the energy consumption, to achieve the ultimate goal for any retrofit project, energy reduction is required. For that, Persily and Emmerich (2012) state that some retrofit measures can support both energy efficiency and IAQ as described in Table 4 which highlights the importance of the whole building approach that engages the building systems interactions.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat recovery ventilation</td>
<td>Maintains rates of outdoor air ventilation, while extracting heat to be used to pre heat or pre cool the supply air. This kind of ventilation is mandatory in some energy efficiency standards.</td>
</tr>
<tr>
<td>Air –economizer</td>
<td>It provides more outdoor, and less mechanical cooling. Not recommended with very polluted outdoor air, or high humidity. Sensors and controls strategy must be maintained.</td>
</tr>
<tr>
<td>On-Demand Ventilation</td>
<td>An obligatory under 90.1 and 189.1, however, it is recommended under 62.1 standards. It provide the adequate ventilation based on the occupancy level, and the CO2 concentration.</td>
</tr>
<tr>
<td>Mixed-mode ventilation</td>
<td>More outdoor ventilation supported with mechanical ventilation when needed. Humidity and outdoor pollutant could be challenging factors.</td>
</tr>
<tr>
<td>Envelope Tightness</td>
<td>IAQ is affected negatively with infiltration, however, moisture dynamic within the envelope needs to be considered.</td>
</tr>
<tr>
<td>Dedicated outdoor ventilation</td>
<td>Provide flexibility in cooling &amp; heating strategies. Good potential to improve IAQ as well as reduce energy consumption. Simple controls, easy to clean and control the outdoor air.</td>
</tr>
<tr>
<td>O&amp;M Decommissioning</td>
<td>Having access to the building access is a key factor. Both good IAQ and energy efficiency can be achieved.</td>
</tr>
</tbody>
</table>

A project was conducted by the U.S. Department of Energy (DOE) in Texas under the name of “Ventilation Effectiveness”, which aimed at highlighting the importance of providing a high performance ventilation system. By doing so, the chance to meet or even exceed the ASHRAE 62.2 standards for air quality and comfort is great with minimal cost. It is found that the projected energy saving in HVAC system could reach 8-10% due to the implementation of effective ventilation systems (US DOE 2015).

### 7 Considerations for Future Buildings' Ventilation Systems

In order to meet the future energy demands in buildings without compromising health, the National House Building Council recommends applying mechanical ventilation with heat recovery (NHBC 2011). However, it is expected that householders may open windows on regular basis seeking for the feel of freshness, which will offset the inherent benefits of such an energy efficient structure that en suite with a mechanical operating ventilation system.

In buildings with mechanical ventilation, long-term maintenance of ventilation systems is one of the biggest issues that may risk the IAQ. It is important to address that integrating design, operating system and occupant behavior is complex interactions that need to be considered in order to improve ventilation in tight houses.

Mechanical ventilation with heat recovery (MVHR) are more energy efficient compared with other systems. It is recommended to install MVHR in new constructed or major
retrofitted buildings. MVHR system requires special attention in all stages: installation, maintenance and operation (Awbi 2015).

As a part of Building Performance Evaluation (BPE) program, a meta study was commissioned to present an outline of the MHVR performance. This technical report (Sharp & McGill 2015) states that a well-designed, installed and maintained system can contribute to good ventilation as well as energy reduction. However, in practice, it is very challenging and requires an overcome of some common problems. Sharp & McGill (2016) list a few of these problems that may appear during the installation stage such as: the imbalance between the extract and the supply airflow. However, in terms of operation, due to its complexity, the occupants may struggle with understanding how to operate and control such a system. For that, Wells et al. (2015) recommends educating occupants when new technologies that are incorporated into buildings.

8 Conclusions

All the recent studies about future buildings expect to witness more energy efficient newly constructed and retrofitted buildings. Achieving balance between saving energy and maintaining healthy IAQ is essential. Although there are some conflicts between the objective of enhancing IEQ, health, productivity and the crucial need to save energy in buildings, there are IEQ strategies that are energy neutral whereas other strategies can provide energy savings as well. The highest priority should be with the strategies that reduce energy consumption (Fisk 2012).

It is recommended to have at least 0.5/hour as an air exchange rate (ach) to help save occupants health and increase their productivity (Awbi, 2015). Moreover, approaching the building retrofit as a holistic project and considering all building systems will maximize the potential of obtaining a better IEQ. The continuous mechanical ventilation is very important in extreme weathers where natural ventilation is not an option. However, mechanical ventilation with heat recovery (MVHR) proved to be the most effective measure to create the needed balance between energy efficiency requirements and a healthy IAQ (Awbi 2015 & Peretti et al. 2015).

There are some factors that may affect the MVHE performance, such as the inadequate design as well as installation, the occupants' lack of knowledge in operating such systems. Addressing these shortcomings by legislators, contractors and homeowners is a necessity to ensure providing the maximum in both energy efficiency and healthy IAQ, which will save money and reduce negative health effects related to IAQ. In general terms, it is very important to increase the public knowledgebase to encourage provision and implementation of the supporting policies and regulations.

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ACHIEVING SUSTAINABLE OUTDOOR THERMAL COMFORT IN THE AMERICAN UNIVERSITY OF SHARJAH CAMPUS

Sarah Al Khawaja1 & Hasim Altan2

1 Sustainable Design of the Built Environment, Faculty of Engineering & IT, British University in Dubai, UAE, sarah.alkhawaja@gmail.com
2 Department of Architectural Engineering, College of Engineering, University of Sharjah, Sharjah, UAE, hasimaltan@gmail.com

Abstract: There are many factors that impact and influence the success of an urban space. Numerous physical and social environment components and location of the given space in the city are all key components that play part. This study however, mainly focuses on one physical environmental aspect known as the thermal environment. Thermal environments are components of physical environments that dictate the human thermal comfort. The control of this comfort is conducted through exchange of energy between the body and its consequent surroundings, and it can generally be stated that it exists in the circumstance that a body can readily sustain a constant and deep temperature of approximately 37°C. Therefore, thermal comfort can be defined as the relationship between the thermal condition and an individual’s awareness of warmth that makes the impression. The study will carry out a comprehensive research on the lay out of the American University of Sharjah (AUS) campus in Sharjah, United Arab Emirates (UAE). Multiple data categories will be collected from the campus users through a series of surveys and interviews to obtain an understanding of the site conditions and their comfort levels. Human thermal comfort is an environmental quality that is directly impacted by the outdoor conditions of the university’s campus. It is among some of the most affected qualities of the environment in the urban outdoors. Since the microclimate of AUS is hot humid, the thermal adaptation of the university’s occupants is quite challenging due to exposure to variation air temperatures. Despite the control the outdoor thermal environment being difficult, there is a need to avail thermal comfortable conditions, which are able to cater for the outdoor activities such as walkability, driving, parking, greenery, shades, water features among others. This study is based on investigating the problem of lack of sufficient thermal conditions to facilitate comfort amongst the University’s occupants. This study examined thermal comfort in open-air of the American University of Sharjah (AUS)’s campus in the UAE. The research started by analysing its layout in relation to architectural elements, climatic conditions and more. It then targeted the common gathering spaces frequented by the students and faculty, and by using means of surveys and interviews, collected data needed for interpreting the personal and actual levels of comfort. Initial results indicated large discomfort levels during summer seasons where users found it difficult to manoeuvre around the campus site. Outdoor activities decreased significantly, thereby rendering large spaces unutilized for the greater part of the year. The study aimed at solving this problem by recommending new improvised design elements for the campus’ thermal adaptation through creating areas with sufficient shades as well as outdoor sophisticated space planning. This hopes to create better functioning and habitable spaces for the students and facility alike.

Keywords: Outdoor Thermal Comfort, University Campus, Sustainable Development, Environmental Adaptation, Microclimate. (up to 5 keywords)
1 Introduction
Thermal comfort is an environmental quality that has a huge impact on the outdoor conditions of the UAE. According to Al Jawarba and Nikolopoulou (2009), thermal comfort can be defined as the relationship between the thermal condition and an individual's awareness of warmth that makes the impression. Outdoor thermal comfort is perceived as a vital factor important in improving quality of life in urban settings. It is a key concern especially since it has significant impact on numerous phenomena such as public health concerns.

Urban spaces form the bedrock for various activities since they dictate the liveability of cities. Thermal comfort experienced by users of open spaces significantly determines the extent of habitability of urban spaces. Cheng (2006) states outdoor ease is simply easy to detect; too cold or too hot. Human thermal comfort is among some of the most affected qualities of the environment in the urban outdoors. However, there are some personal factors such as clothing and level of activity that also have an impact on thermal comfort. According to Angelotti et al. (2007), through modifying patterns of carried out activities and clothing used, people are able to adapt to ambient thermal conditions.

The thermal adaptation of the city's occupants is quite challenging due to exposure to variant air temperatures. Despite the control the outdoor thermal environment being quite difficult, there is a need to avail thermal comfortable conditions, which are able to cater for the outdoor activities such as walkability, driving, parking, greenery, shades, water features among others (Smith and Levermore 2008).

In the United Arab Emirates (UAE), circumstances of an unshaded courtyards or open spaces are known to be very unsuitable during the daytime hours due to extreme heat and humidity conditions. This study is based on investigating the problem of lack of sufficient thermal conditions to facilitate comfort amongst the city's occupants. It asserts to solve this problem by recommending a new improvised design for a certain part of Sharjah, that will encompass elements for thermal adaptation for instance through creating areas with sufficient shades and vegetation, as well as outdoor sophisticated space planning. Each and every setting must be studied and designed well when it comes to achieving thermal relief.

This study aims to examine thermal comfort in open-air of the American University of Sharjah (AUS)'s campus in the UAE.

2 Literature Review
Sharjah, a city in the UAE, located in the southeast end of the Arabian Peninsula along the Arabian Gulf northern coast, is characterized by typical hot and arid climatic conditions. It has mild warm winters boasting 23 degrees' temperature highs, and warm humid summers reaching up to 42 degrees (Dubai Airports 2015).

Since the climate of the city is defined by two distinctive seasons; winter and summer, with summer being more dominant, external activities tend to be exhaustive on a human body, and outdoor users tend to feel very hot and uncomfortable during the majority of the day, with heat stress being usually anticipated (Ahmed and Shaikh 2013).

Interest in measuring thermal comfort has increased recently owing to the climate changes and augmented heat stress in cities. Four major climatic parameters can be used to define thermal comfort: air humidity, ambient air temperature, airstream velocity and radiant
temperature (Behzadfar and Monam 2011). In theory, these parameters can be applied to outdoor surroundings as well. The key challenge for measuring thermal open-air conditions is that climatic variables may be increasingly diverse in contrast to indoor environments, as they ought to use human factors (metabolism and clothing) and meteorological variables (temperature of the air, radiation, the speed of wind, humidity) as well.

Figure 1: Variation in Human Comfort with respect to changes in Temperature and RH (Shakir 2009)

Shakir (2009) has stated that these other factors can be psychological factors, and human adaptability can affect how a person feels, thus bringing about different levels of comfort. Fig.1 above indicates how the level of human comfort tolerance is affected when an inter-relation between different environmental factors, such as temperature and relative humidity, occur. Certain elements play a role in reducing the heat/solar impact on outdoor spaces, and vegetation has shown a significant effect on the atmosphere in urban regions. Its relative absence in numerous urban areas has been referred to as one of the primary drivers of increased urban heat (Berry et al. 2013). According to Giridharan et al. (2005), wind, infrared radiation and solar radiation are essential to open-air relief of human beings in urban open-air spaces, and can be regulated through site design. Trees and other flora can be used as a means to provide shade to decrease solar energy input to the user’s body.

In a study conducted by Morakinyo et al. (2013) evaluated the effect of vegetation on the thermal condition in and around two distinctive buildings (Building A and Building B) (Fig.2) on a university campus in Nigeria for period of six months.

Figure 2: The two buildings of the university campus in their outdoor conditions (Morakinyo et al. 2013)
The university, the Federal University of Technology in Akure, experiences a warm and humid climate. In their study, two buildings of comparable designs and layouts were selected for analysis. One building had vegetation surrounding it while the other was not. Their impact was analysed in regards to indoor and outdoor thermal comfort for a period of six months. Results indicated that Building B users were less comfortable during daytime. Furthermore, the outdoor environment around Building A is more thermally comfortable during all seasons. The study points toward the requisite for greening as a way of improving thermal comfort regardless of the region.

It is important to note that thermal comfort is a psychological elucidation of the body’s physiological state and is not the same as temperature sensation (Lide 2010). For instance, people who are seated or resting have different thermal perception than in when a person is active. The heat exchange between the body and the surroundings can occur in different ways. Therefore, this research aims to determine the relationship between human thermal comfort and different physical components of urban outdoor spaces through their effect on the environmental components.

3 Methodology

This study is adopting a case study to answer the research questions raised, and accordingly, selected a site that is a measurable scale, as well as have the characteristics of a city, hence, the American University of Sharjah campus was found to be suitable (Fig.3).

![Figure 3: The American University of Sharjah campus (AUS 2016)](image)

This study used a mixed methodology, which combines both qualitative and quantitative research approaches. Quantitative method helped in addressing the objectives of the main study through empirical assessments. Using various numerical measurements and analysis, it was also possible to achieve findings through statistical entities. Furthermore, this approach provided scope for a large number of respondents for assessment in the study (Saunders et al. 2009). Qualitative method on the other hand was applied in order to help with the collection of exploratory data in a more organized form (Creswell and
Plano Clark 2007). The applied data collected methods used in the case study are: Social Surveys (questionnaires); Field (site) study; and Interviews.

Quantitative methodology took place in the form of surveys, questionnaires and climatic data collection on site. The surveys were aimed at the student level of the campus users since they are the population that makes most use of the outdoor spaces. Questions targeted different aspects such as frequency of site usage, duration, and type of clothing, all elements that affect the thermal comfort level. On the other hand, interviews took place with the university faculty as to obtain a professional more specific point of view on the subject matter. Faculty interviewed were from the College of Architecture.

Quantitative data analysis has been carried out using tables and graphs using Microsoft Office Excel. Interview guides data was analysed qualitatively. Pertaining to each research question qualitative analysis was done alongside quantitative analysis. Furthermore, it was important to conduct on-site measurements to understand the conditions of the university campus. Schematic figures and analytical diagrams were completed to show and study different aspects of the site. Site analysis/diagrams have been completed by combinations of hand sketches and computer generated drawings with the aid of software packages, such as Adobe Photoshop and AutoCAD.

4 Results, Analysis and Discussion

In order for understanding the usage and the density of the AUS campus, it was crucial to conduct on-site analysis and to also study the effects of the space it has on the users. The study timeframe was split into two seasons, summer and winter, where temperature collection, surveys and interviews were taken place in order to provide accurate and detailed results.

4.1 Analysis of the Space

AUS campus is of a relatively large scale, with 1,340,000 m² of land, and over 4000 students present at any given term of the year. It is surrounded by a fence, and has only two car/motor main accesses. With parking spaces allocated far from the college buildings, users mainly depend on pedestrian circulation for moving around. The large open spaces of the campus create an unfriendly atmosphere that is a haven for the harsh climatic conditions.

The study took into account the materials used on campus; hardscape and softscape, the space compositions, buildings width to height ratio, and sheltering elements. Fig.4 shows the above-mentioned elements with respect to their location on campus. Based on these, the surveys were shaped and results were obtained accordingly. Despite the large areas available on the campus, the greenery and vegetation is mainly found in spaces that are not frequently used by the students and faculty, such as the sports fields and dormitories, and are not shaded, and the campus does not offer many artificial human-made shaded areas or elements, such as pergolas. The main plaza and buildings, as marked on Fig.4 (1 to 7), is completely exposed and made out of marble, which is very absorbent to heat and solar radiation. Furthermore, the scale of the walkways and paths between buildings are quite wide. Some of these paths are lined up with palm trees that are too large of a scale to provide sufficient shade (Fig.4 marked as 5), and are placed in a grid-like manner that makes it uncomfortable to pass through. Space composition plays a role on the outdoor temperature, and remains dependent on all other factors, such as H:W (Height to Width) ratio of the buildings’ form.
4.2 Climatic Data Collection
Climate data of Sharjah was not readily available through research and inspection. Therefore, the study based on Climatic weather data of Dubai, a city that shares borders with Sharjah and has roughly the same weather conditions throughout the year. The data in Fig.5 based on the average temperatures found in Dubai across the year, with August being the peak hottest where high temperatures above 45°C are recorded, and December the coldest month with temperatures as low as 5°C are noted.
The dominant wind direction comes from the North-West, as can be noted from the Wind Rose in Fig.6. The highest recorded is 2.7 to 5.5 m/s. However, due to the open geographical nature of the city, low wind levels blow from different directions throughout the year.

Based on the climatic analysis conducted above, the data collected was applied to the AUS campus in order to understand the impact the outdoors thermal conditions have on the users themselves.
### 4.3 Survey Results and Analysis

Based on the site and climatic data of the case study, the survey was formulated using the described conditions as tabularized in the following table (Table 1):

<table>
<thead>
<tr>
<th>Site properties</th>
<th>- Large open areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Lack of shade</td>
</tr>
<tr>
<td></td>
<td>- Large H:W ratio of buildings</td>
</tr>
<tr>
<td></td>
<td>- Minimal water features</td>
</tr>
<tr>
<td></td>
<td>- Minimal vegetation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Median outdoor temperature [Summer]</th>
<th>42°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median outdoor temperature [Winter]</td>
<td>23°C</td>
</tr>
<tr>
<td>Relative humidity [Summer]</td>
<td>60%</td>
</tr>
<tr>
<td>Relative humidity [Winter]</td>
<td>30%</td>
</tr>
<tr>
<td>Wind direction [Summer]</td>
<td>Wind circulated in all directions</td>
</tr>
<tr>
<td>Wind direction [Winter]</td>
<td>North-West</td>
</tr>
<tr>
<td>Sky conditions [Summer]</td>
<td>Sunny clear with no clouds</td>
</tr>
<tr>
<td>Sky conditions [Winter]</td>
<td>Clear with a few clouds</td>
</tr>
<tr>
<td>Timings</td>
<td>Morning: between 8 am and 11 am</td>
</tr>
<tr>
<td></td>
<td>Afternoon: between 3 pm and 6 pm</td>
</tr>
<tr>
<td>Site Materials</td>
<td>The campus ground surface is made up of Granite and Marble</td>
</tr>
<tr>
<td>The geographical position</td>
<td>Sharjah, UAE. Latitude: 25.25°, Longitude: 55.33°</td>
</tr>
</tbody>
</table>

A total of 46 students have participated in the survey while using the outdoor spaces of the campus. 24 were surveyed in the winter season, and the remaining 22 in the summer season. The survey was broken down into different sections, analysing their genders, ethnicity, clothing types, activities. Questions that are more detailed came into account about thermal sensations, humidity, wind, comfort and relief from heat. Figure 7 below shows a sample of the results obtained regarding solar intensity, and how respondents felt during both seasons. Summer sun intensity was very strong causing discomfort to the students. However, winter responses varied greatly as users were found to tolerate the sun intensity by a large difference.

![Figure 7: Sun tolerance](image-url)

As can be deduced from such results, sun position (angle) plays a large role in determining the outdoor thermal comfort levels, as it affects the solar radiation, intensity and shading levels.
Using the Stereographic diagram and the AUS campus map with reference to the Main Central Building, the analytical diagram in Fig.8 indicates the sun path and location, and the solar intensity it has on a part the site during the month of June. Most open spaces are exposed to direct solar rays, making simple tasks such as walking between buildings a big discomfort. The site flooring material absorbs a large amount of the solar heat, causing a rise in the temperature on the already hot site.

In Fig.9, during the winter season, results vary greatly as the solar intensity is reduced to the low altitude angle of the sun, thus reducing radiant temperatures, making the outdoors more comfortable.
Air movement also plays a role in determining the level of outdoor comfort. According to the survey results, as indicated in Fig.10, most summer respondents found the wind to be stale and dry. This decreases the comfort levels and as it does not aid in reducing the humidity. However, in the winter survey results, students found the airflow to be much higher and cooler, therefore, a more convenient outdoor environment for them.

The vast and far apart orientations of the buildings are also factors in minimizing shade and channelled wind that would help lessen the heat and humidity intensity. The AUS campus is a typical case of an under-designed site in regards to the outdoor thermal conditions.

An overall summary of the survey responses regarding acceptance of the thermal environment found that in both seasons, results were split into almost equal responses as shown in Fig.9. Most summer respondents, 21 of them, found the outdoor conditions unacceptable. On the other hand, winter respondents were satisfied with the weather conditions. This indicates, with the previously discussed climatic elements in accordance to AUS campus, the main discomfort comes during the summer season; however, improvements have to be carried out on the site in order to have a better and more comfortable thermal outdoor conditions.

4.4 Discussion and Findings

It was concluded that the areas with open exposed spaces, even with the existence of Palm trees around, had the highest temperatures during summers and winters while the more closed spaces had much lower temperatures and higher wind speeds, making them more thermally comfortable. The following recommendations are deduced based on the site and survey analysis:

- Provide adequate shading;
- Allow for adequate airflow through zoning the building and adding mechanical equipment for increased air movement;
- Change to flooring material that has low thermal storage capacity;
- Provide misters/low-energy fans in high-use areas;

![Figure 11: Acceptance of thermal environment](image)
Site climatic elements such as solar radiation, temperature, humidity, and wind can be controlled, or simply manipulated, through properly analysed site design. Certain design strategies for achieving thermal outdoor comfort are discussed as follows:

**a. Shade**

As can be noted in Fig.12, the existing trees around AUS campus are mainly Palm Trees. Their placement and size are not helping in reducing heat and providing good shade. Thereby, wider trees are proposed in Fig.13 instead to provide a narrower and human related scale.

![Existing trees scenario around the AUS campus](image)

![Proposed trees scenario around the AUS campus](image)

Fig.14 shows a comparative analysis of local type of trees that can be used on the AUS campus. Even though that the palm tree has the wide leaves, they are largely spaced apart, and do not provide enough shade as compared to the Rolla or Ghaf tree.

![Comparison between local trees in the UAE that can be used on the AUS campus](image)
b. Wind

Most of the campus consists of spaces that are very open and have wide circulation paths. The building height to path width ratio plays a major role in determining the frequency and entrapment of airflow among outdoor spaces. The analysis conducted, as seen in Fig.15 to 17, the wider the path width, the lower are wind entrapment possibilities.

![Figure 15: Building height to path width - Width to Height ratio high](image)

![Figure 16: Building height to path width - Width to Height ratio medium](image)

![Figure 17: Building height to path width - Width to Height ratio low](image)

In theory, to enhance the wind circulation on campus, the buildings would actually have to be "moved" to create narrower paths, bringing them closer together and make the paths more of a humane scale.

Therefore, the proposed solution would be to install pathways that would have shading structures, oriented towards the wind direction to force the breeze in and have cooler areas. Cooling spots with seating installed to make use of the open spaces that are practically wasted. A schematic design sketch, as shown in Fig.18, simply shows how a preliminary solution can be integrated within the exiting campus.
Figure 18: Sample-shading paths to reduce the large scale on the AUS campus plaza - Plan

Hence, the presence of any kind of shading, whether by artificial mesh or by trees, comfort levels would increase, and uneasiness is tremendously reduced for a certain period of time, as extreme harsh conditions are being avoided when any kind of covering was situated above open paving (Robitu et al. 2006). When shading elements are merged with vegetation, both systems produced pleasant conditions at most the hours of the day no matter the severity of temperature. In addition, pavements with shaded grass receive a lower radiating temperature on the surface level.

5 Conclusions

Outdoor thermal conditions are physical environment aspects that dictate on the thermal human comfort. This comfort is controlled through exchange of energy and heat between the human body and its consequent environment.

The study was based on examining the problem of lack of adequate thermal conditions to enable comfort among the dwellers of AUS. The predictions of effectiveness were more through the extensive analysis of the data collected, interviews conducted by experts in the field, and personal interaction on the site itself during both winter and summer seasons.

Air temperature, wind, relative humidity, clothing, site materials, orientation and more were factors that were considered in the study. It is important to observe all this factors when designing an outdoor thermal environment. There should be minimum access to solar radiation when cooling is required. The outcomes recommended are to enhance the current design and integrate elements onto the existing campus. Simple improvements would make large differences, such as adding modular aspects that can be repeated around the campus, therefore achieving higher outdoor thermal comfort.

References


AN OVERVIEW ON BUILDING INTEGRATED PHOTOVOLTAIC FAÇADES: AN ARCHITECTURAL PERSPECTIVE

Daniel Efurosibina Attoyé, Kheira Anissa Tabet Aoul & Ahmed Hassan

1, 2, 3 Department of Architectural Engineering, United Arab Emirates University, UAE,
1 201590088@uaeu.ac.ae, 2 Kheira.Anissa@uaeu.ac.ae, 3 Ahmed.Hassan@uaeu.ac.ae

Abstract: One raging question asked globally is how to address the energy challenge; a quest for modernization, industrialization and sustainable development. Globally speaking, over 40% of energy consumed is related to buildings. Architects and building developers are professionally responsible for the transformation of the natural environment into the built environment. Strong advocacy for an architectural approach which embraces renewable energy solutions as a priority is therefore of immense importance to both humanity and the environment. This paper focuses on an overview of a contemporary method of incorporating renewable energy into the building envelope i.e. Building Integrated Photovoltaics (BIPV). It details strategic environmental, economic and design benefits; and the multi-functional means of applying BIPV products using several global examples. Using the hot climatic region as a case study, a comparison is made between the field investigations on BIPV facades, with some architectural and sustainability issues. This comparison puts in context the direction of BIPV research in relation to architectural applications. The study highlights an inspiring challenge to researchers on the areas of sustainability which have not been sufficiently investigated within the present BIPV technological discourse. In conclusion the paper reflects on the opportunities and challenges of BIPV, and proposes a few recommendations which need to be addressed in advancing a greater global acceptance of renewable technology, specifically BIPV in 21st century architecture.

Keywords: Building Integrated Photovoltaics (BIPV), Façade, Architectural Integration, Hot Climate
1 Introduction

Energy, water, waste, design, materials are some of the principal focus in sustainable architecture (Sassi 2006) and these can be expressed both at a building or city scale. When resource exploitation and ecological impacts are significantly reduced; long term socio-economically and ecologically sustainability can be achieved (Martos et al. 2016). By using methods which integrate and mitigate the effect of selected design strategies on the environment, this architectural approach creates a space which promotes a better quality of life for people (Martos et al. 2016; Dassen et al. 2013).

Buildings are a main source of global energy consumption and CO₂ emission; accounting for about 40% of earth’s yearly energy consumption (World Energy Council 2016) thus the manner they are designed is of grave importance. Building Integrated Photovoltaics (BIPV) technology as an advancement in photovoltaic (PV) technology which provides an innovative strategy leading to more energy-efficient buildings. One of many examples is presented in a study which reflects a reduction of energy consumption and an increase in energy efficiency by electricity generation and shading using BIPV (Pagliaro et al. 2010) Technological advancements has evolved BIPV into a PV application with the capability of electrical delivery at a comparatively less cost than grid electricity for certain end users in certain peak demand niche markets (Norton et al. 2011).

As an elegant tool available to architects, BIPV serves simultaneously serving as a part of the building envelope material and energy source. BIPV systems can be more cost effective simply because their composition and location replaces a number of conventional components. They thus provide savings in materials and electricity costs, at the same time reduce use of fossil fuels and carbon and greenhouse gases emissions and improve the architectural image of the building (Agathokleous & Kalogirou 2016). This savings in material is one dimension of sustainable design. The objective of this paper is to highlight the various applications of BIPV as a contemporary building material used in facades and relate this to investigations in hot climates as these align with current sustainability issues.

2 BIPV Functions and Application

From a more general functional point of view, BIPV can function as roofing, cladding, glazing or shading system (Jelle 2015; Munari et al. 2013; Farkas et al. 2013; Heinstein et al. 2013; Montoro et al. 2011; Thomas 2003). Apart from the fundamental production of electricity the multi-functionality of BIPV means it can fulfil many tasks as a facade or roof element such as solar protection, glare protection, as well as PV-system integration for electricity. The following is a non-exhaustive list of the multiple functions that BIPV modules can perform:

2) Heat protection/Thermal insulation (heating as well as cooling) -improving the efficiency of cells by cooling through rear ventilation (Jelle 2015; Heinstei n et al. 2013; Montoro et al. 2011).
3) Visual cover/ refraction -one-way mirroring visual cover (Farkas et al. 2013; Montoro et al. 2011).
4) View and Daylighting -semi-transparent options allow for light transmission and contact with exterior (Montoro et al. 2011; Pagliaro et al. 2010; Oliver & Jackson 2001).
5) Aesthetic quality -integration in buildings as a design element (Jelle 2015, Montoro et al. 2011).
6) Safety –applied as safety glass (Montoro et al. 2011).

Plate 1: King Abdullah Petroleum Studies & Research Center (KAPSARC), Riyadh, Saudi Arabia; showing BIPV applications (Source: http://vista-eco.com/projects/kapsarc-photovoltaic-facade-ryadh/)

The building facade is conventionally made of up walls, glazing, cladding and fenestrations; and other structures like shading devices, parapets, balconies. Each of these provides positions in the building for integrating PVs. Specific to facades, there are generally a few basic ways of integrating PVs in buildings according to several studies (Jelle, 2015, Munari et al. 2013, Farkas et al. 2013, Heinstein et al. 2013, Montoro et al. 2011, Thomas 2003):

- **Cladding systems:** this field of BIPV application include facades where solar panels of can be integrated as a conventional cladding system for curtain walls and single layer facades. (Heinstein et al. 2013). Examples are Opaque - cold or warm façades, Semi-transparent and translucent façade parts (Munari et al. 2013).

Plate 2: BIPV Façade examples

(A) Façade Cladding of Copenhagen Towers Hotel, Denmark; showing custom-made crystalline PV integrated into east, south, and west facades; (B) Curtain Wall of Guangdong Hanergy, China

- **External Devices** such as Sunshades and sunscreens, spandrels, balconies parapets, elements of visual and acoustic shielding (Montoro et al. 2011)
Advanced/Innovative Envelope and Special External Devices Systems. (Munari et al. 2013); such as double skin facades, active skins, rotating or moving façade parts etc.

2.1 Strategic Benefits
From an architectural, technical and financial point of view, BIPV advantages include (Norton et al. 2011)

- Reduction in the associated Balance of System (BOS) and possible system oversizing when grid-connected stand-alone solar farms are setup
- Reduction of investment costs by displacing facade/roof/shading elements;
- Aesthetical appeal
- Suitable for unshaded roofs and facades in densely populated areas;
- No additional land area required, since building surfaces used as PV mounting structure;
- Ability to be designed to generate electricity at a building’s peak usage times particularly for commercial buildings, thus reducing the building’s peak grid electricity demand;
- Able to satisfy all, or a significant part, of the electricity consumption of buildings.
2.2 BIPV Assessment

Skandalos & Karamanis (2015) maintain that performance evaluation of BIPV—with respect to glazing, should cover four main aspects:

- Electrical performance
- Optical performance
- Thermal performance
- Energy saving potential, cost reduction and environmental benefits.

This opinion is deduced from various research investigations in various parts of the world and is indicative of the fact that an assessment of BIPV potential is closely related to these areas of interest—some directly, some others indirectly. Table 1 shows a reference to some studies which reflect a comparison of BIPV performance under specific conditions in view of certain factors related to sub-categories of performance.

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<thead>
<tr>
<th>Assessment Aspects</th>
<th>Assessment Sub-Categories</th>
<th>Sample Factors</th>
<th>Sample Assessment Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Electrical</td>
<td>Shading and Tilt Angle (Song et al. 2008; Yoon et al. 2011);</td>
<td>Simulation studies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Orientation (Robinson &amp; Athienitis, 2009; Ng et al. 2013)</td>
<td>Numerical models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operating Temperature And The Properties Of The Back Side Glass (Park et al. 2010; Guardo et al. 2009)</td>
<td>Mathematical approximations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transparency (Yoon et al. 2011)</td>
<td>Scaled models</td>
</tr>
<tr>
<td></td>
<td>Thermal</td>
<td>U And G Values, Glazing Layers (Chow et al. 2010)</td>
<td>Full-scale models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell Area (Fung and Yang, 2008)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SHGC (Wong et al. 2008)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air Gap (Peng et al. 2013; Fossa et al. 2008)</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Daylighting</td>
<td>Degree Of Transparency (Miyazaki et al. 2005; Kang, 2013; Olivieri et al. 2014)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Window To Wall Ratio (Miyazaki et al. 2005)</td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>Energy Saving</td>
<td>Cooling Reductions (Lu &amp; Law, 2013)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heating And Cooling Reductions (Radhi, 2010; Miyazaki et al. 2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emissions Control</td>
<td>(Li et al. 2009)</td>
<td></td>
</tr>
</tbody>
</table>

3 Investigations in Hot Climates

The application of PV technologies as power generation devices in the built environment has many benefits. There are however a number of investigated factors that impact upon the design and performance of BIPV. These factors include operating temperature, low irradiation quantity; component optical losses and changes of sun spectral (Tripathy et al. 2016). In hot environments more considerations include the harsh hot climatic, the maintenance and cleaning issue especially the dust accumulation, the inclination angle sensitivity, the importance of considering diffused sunlight, the potential of using flexible PV, the advantage of solar shading PV, life time issues, and aesthetics. (Al-Sallal et al. 2013). To highlight some specific hot climatic characteristics two examples have been selected, solar radiation and dust.

i. Solar irradiation and access:
Solar access is the incidence of solar radiation (insolation) that reaches a PV surface at any given time, determines the potential electrical output of a BIPV system (Eiffert & Kiss 2000). The yearly sum of global is specific to the site location for the project. In hot climates the solar radiation is about 1000kw/hr/yr.

ii. Dust and Partial Shading
System performance can be affected by even partial shading of the PV modules; leading to significant efficiency losses in the system output. The presence of barriers or obstacles such can often present a difficult problem (Munari et al. 2013; Thomas 2003). In hot climates, the desert dust is driven by strong winds across both rural and urban areas; leading to a formation of a dust coat on the PV panels and reducing the electrical conversion efficiency.

BIPV investigations generally fit into one or more of a number of areas. These “study blocks” are shown in Fig. 1 and represent an overview of the most studies.

3.1 Overview of Hot Climate BIPV Façade Experiments
This section summarises examples of BIPV facade studies in hot climates; with specific focus on outdoor experiment which investigate performance in field experiments. Table 1 shows a selection of these studies alongside an overview of the application architecture integration and sustainable aspects.
## Table 2: Summary of BIPV façade investigations

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location / Country</th>
<th>Objective</th>
<th>Class of BIPV Product</th>
<th>Class of BIPV Focus</th>
<th>Sustainable Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radhi (2010)</td>
<td>Wall cladding / UAE</td>
<td>Energy analysis of facade-integrated photovoltaic systems applied to UAE</td>
<td>BIPV Module; BIPV Glazing</td>
<td>Performance and Optimization; Cost;</td>
<td>Energy Design</td>
</tr>
<tr>
<td>Elarga et al. (2016)</td>
<td>Double Skin Façade / UAE</td>
<td>Performance and energetic improvements due to installation of semi-transparent PV cells</td>
<td>BIPV Foil; BIPV Module</td>
<td>Performance and Optimization; Architectural Integration;</td>
<td>Energy Design</td>
</tr>
<tr>
<td>Hasan et al. (2014)</td>
<td>Wall / Pakistan</td>
<td>Energy and Cost Saving of a Photovoltaic-Phase Change Materials (PV-PCM) System</td>
<td>BIPV Module</td>
<td>Performance and Optimization; Cost;</td>
<td>Economic Energy Design</td>
</tr>
<tr>
<td>Hasan et al. (2015)</td>
<td>Wall / Pakistan</td>
<td>Increased photovoltaic performance due to temperature regulation by phase change materials</td>
<td>BIPV Module</td>
<td>Performance and Optimization;</td>
<td>Energy Design</td>
</tr>
<tr>
<td>Alnaser et al. (2008)</td>
<td>Wall / Bahrain &amp; Window / Bahrain</td>
<td>Potentials and Practicability BIPV retrofitting examples</td>
<td>BIPV Foil; BIPV Module; BIPV Glazing</td>
<td>Architectural Integration; Cost; Market;</td>
<td>Economic Energy Design</td>
</tr>
<tr>
<td>ElSayed (2016)</td>
<td>Ventilated Double Skin Façade / Egypt</td>
<td>Optimizing thermal performance of ventilated BIPV for upgrading informal urbanization.</td>
<td>**</td>
<td>Performance and Optimization; Architectural Integration; Environmental Impact</td>
<td>Energy Design</td>
</tr>
<tr>
<td>Bahr (2014)</td>
<td>Window Blinds / UAE</td>
<td>Energy, Cooling and Cost analysis of BIPV blind system</td>
<td>BIPV Module</td>
<td>Performance and Optimization; Architectural Integration;</td>
<td>Energy Design</td>
</tr>
</tbody>
</table>

Based on a survey of notable journals, only a handful of field investigation are representative of BIPV façade studies in the region. The table shows that most of several of these studies are in the UAE and focus on performance and optimisation of the BIPV façade with a few on architectural integration and environmental impact. In terms of the sustainable aspects, more attention has been given to energy and design considerations. This may be the result of emphasis on a balance manage the extreme weather conditions. In the various studies, the BIPV module is the product most of frequently investigated. BIPV products can be grouped based on how the manufacturer describes the product and what other type of material the product is customized to be combined with. They include BIPV tiles, BIPV foil (Thin film), BIPV modules, BIPV glazing products (Jelle 2015; Nikolić et al. 2014; Jelle et al. 2012). The emphasis on this product is due to its ease of application in the region. As there are seldom pitched roofs, BIPV tile products are not frequently used. Regarding the sustainability emphasis, all the studies focus on energy and design aspects with a few on economic and environmental. While this may lead to more efficient
systems, they may also lack in socio-environmental considerations; such as poor public awareness and appreciation of BIPV systems.

4 Challenges and Future Opportunities

Transparency, Temperature Dependency, Initial Comparative Cost, Technological Life Span (TLS), Maintenance, thermal management and aesthetics are some of the challenges associated with BIPV facades. Investigation into these is indeed of importance. Optimization strategies –being the focus of much research asserts that the power output of BIPVs can be improved around 5% at Standard Test Conditions depending on the module type with the proper passive cooling. Apart from passive cooling, concentrating technology can be an attractive alternative as a consequence of the solar intensity dependency of module temperature (Cuce & Cuce 2014).

The cost and efficiency of a BIPV system can be lowered by reducing PV module and component manufacturing costs, installation costs, operation and maintenance costs and improving PV and other component efficiencies (Norton et al. 2011). The main bottleneck discovered during a BIPV study conducted in a European research project, was in the ability to communicate this enhanced value and the new possibilities to customers and thus justify the higher cost (generally an increment around 20% (Pagliaro et al. 2010).

The extensive research and global interest in BIPV over the last one decade is not likely to abate. Areas like daylighting, self-cleaning PV glazing, and aesthetics using colour, form or shapes are a few fertile areas. With shifting policies, government tariffs and policy changes, it will be also interesting to investigate the possibility of using demonstration projects in certain regions as a push for BIPV wide acceptance.

5 Conclusion

This paper presents an overview on BIPV façade applications and investigations. An overview of investigations in hot climates reveal that more studies focus on performance optimization of BIPV and less on architectural integration. It also shows that energy and design aspects of sustainability are the core emphasis. While this leads to more efficient BIPV façade designs, it may impede on satisfaction on consumer preferences and the general public perception. In view of the fact that fewer studies focus on economic and social sustainability aspects of BIPV investigation, further research is advocated in these areas. This will advance BIPV sustainability, facilitate public understanding and acceptance of BIPV, as well as advance its market penetration.

Acknowledgement

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References


DEVELOPMENT OF A BUILDING INTEGRATED PHOTOVOLTAICS - MASS CUSTOM HOUSING INDEX

Daniel Efurosibina Attoye¹, Kheira Anissa Tabet Aoul², Ahmed Hassan³

¹²Department of Architectural Engineering, United Arab Emirates University, UAE
¹ 201590088@uaeu.ac.ae, ² Kheira.Anissa@uaeu.ac.ae, ³ Ahmed.Hassan@uaeu.ac.ae

Abstract: The strategic potentials and benefits of Building Integrated Photovoltaics (BIPV) have been definitively asserted in several major reviews carried out by researchers over the last few years. Several of them point to the veracity of this technology as an elegant architectural and aesthetic option with smart energy saving potentials for building developers, thus, asserting its importance as an energy-efficient strategy to achieve sustainable building design. Similarly, investigation into Mass Custom Homes has started addressing its zero-energy potential and taking advantage of this unique opportunity to actualise the client's brief, without compromising standardisation. Although a link has been established in literature between BIPV and zero-energy homes, an index of BIPV resources outlining materials, functions and products is essential to create a BIPV-Mass Custom synergy. This paper aims to present the development of an original index tool which reflects BIPV standardisation and customisation potential along with an outline for its evaluation. The strategic impact of the BIPV index reflects architectural, energy and environmental benefits. It also presents architects and planners with an easy-to-use tool in BIPV implementation, and can be used as a strategic means of advancing the acceptance of BIPV among building clients. The index further achieves a distinctive inclusion of renewable options for mass custom housing schemes with multiple advantages and opportunities for future innovation.

Keywords: Building Integrated Photovoltaics (BIPV), Energy, Index, Mass Custom Homes
1 Introduction

Building integrated photovoltaics (BIPV) systems involve solar cells which are integrated within the building envelope, in order to generate electricity through incident solar radiation (Jelle 2015; Nikolić et al. 2014). BIPV can be integrated into the building envelope as part of the building structure; by substituting conventional building materials rather than adding them afterwards (Montoro et al. 2011). BIPV’s multi-functional potential has been highlighted by several researchers (Jelle 2015; Farkas et al. 2013; Heinstein et al. 2013; Tabriz et al. 2011; Montoro et al. 2011; Oliver & Jackson 2001). Apart from serving as a clean, local power source, BIPVs present environmental, economic, social and design benefits which will be further outlined in this paper. Typically, architects and clients have unique tastes or objectives during the design process. Some are cost or aesthetically-driven, while others seek to meet sustainability. The process of customisation is thus an intrinsic part of the design process. This paper seeks to explore the potentials of a BIPV-Mass Customisation synergy.

In succinct terms, mass customisation is a complex oxymoron which strives to combine mass production and customisation (Noguchi & Hernández-Velasco 2005; Noguchi & Hadjiri 2009). The concept, pioneered by Stanley Davis and Alvin Toffler (Davis 1987; Toffler 1970), is a strategy aimed at competitiveness in customer-oriented markets with the goal to satisfy the individual needs and wants of consumers of products (Andújar-Montoya et al. 2015). In the housing sector, the concept focuses on the standardisation of housing components such as building materials and systems, rather than the whole house. This ideology of ‘parts standardisation’ engages customers in the process of specifying and selecting standard ‘housing components’ based on specific preferences (Noguchi & Hernández-Velasco 2005). Mass customisation as a strategy may allow for choice of product description (different options in accessories and colours) or payment as a means of meeting wide and varied users’ needs (Shin et al. 2008).

The integration of photovoltaics in buildings was debated as a standard feature in optional housing designs due to certain perceived disadvantages such as the complexity of the buying decision (Barbose et al. 2006 in Noguchi & Hadjiri 2009). This may relate in part, to the multiple technical decisions necessary which ultimately determine the BIPV system performance. However, its clean energy advantage coupled with present global energy challenges have fuelled a substantial market expansion. Yet, one other reason for which BIPV is held back in some regions is a lack of awareness and comprehension among some architects, planners, the general public and other stakeholders (Yang & Zou 2016; Farkas et al. 2013; Heinsein & Jackson 2013). In order to facilitate stakeholder acceptance, architects require a tool which defends the technical as well as architectural potential of BIPV by simplifying the process of customisation and application. The possible benefits of a potential synergy between BIPV and Mass customisation, includes a list of social, economic, environmental and design advantages. Armed with this knowledge, stakeholders – particularly architects - will be able to characterise, customise and fulfil the housing consumers’ taste, as well as assist investors in determining the BIPV market direction. In addition, the synergy will combine the strategic benefits of both the BIPV technology and Mass customisation. It will also stimulate the growth of both with sustainable development from an energy and social perspective as these represent the respective primary goals of these two (2) design approaches.

This paper represents an on-going research which seeks to develop a tool to aid clients and architects in customising BIPV products to suit their needs and preferences. It focuses on product customisation of the PV modules leading to a collection of prototype BIPV façade designs.
2 Mass Custom and BIPV Technology Overview

Mass production and customisation have fundamentally conflicting aims that are widely reviewed in specialised literature. In clarifying this, a pioneer in the field, Noguchi (2005) developed a model to highlight the interaction of a product sub-system (consisting of location, personnel and tool components) and a service sub-system (consisting of volume, exterior, interior and other components) for mass custom homes. The model highlights the process of allowing customers to personalise their homes based on their design preferences prior to production. In parallel, Duarte (2005) designed an interactive computer system based on a discursive grammar established from a distinctive program and design (or shape) grammars both of which will ultimately integrate design and production systems. Improving on this, Duarte & Benros (2009) replaced the shape grammar used to codify the rules of the design system with a parametric design tool which better meets the goals and constraints of architectural design. More recently, research demonstrated that the nature of designing mass-customised products involves a shift of emphasis from designing a particular form with a discrete set of dimensions, to a parametric system that can produce a wider range of designs (Kolarevic 2015). The process provides close contact to costumers and product developers, and creates an avenue for the conceptualisation of attractive building products (Tillmann et al.. 2015).

Although mass custom homes may theoretically achieve a high level of standardisation of all housing components that homebuyers can directly select in customising their new home, user choices of mass-produced and standard components paradoxically increase the level of customisation in housing design (Noguchi & Hernández-Velasco 2005). In practice existing elements (i.e. parts of a whole) of a building can be standardized then, multiple combinations of these parts can be created with a great opportunity for creativity (Noguchi & Hadjiri 2009) and reduction of production costs by achieving the economies of scope (based on standardisation of housing components). While helping to totally customise homes in response to clients’ demands for their new home (Noguchi & Hernández-Velasco 2005), the approach also gives mass-produced houses some of the qualities associated with individually designed homes (Duarte 2005).

2.1 BIPV Technology: Potentials and Application

The economic and environmental potentials of BIPV add to its inherent energy-saving and design benefits. The economic benefit of BIPV includes conservation of land used for utility-scale PV installations (Yang & Zou 2016; Byrnes et al. 2013), reduction in material, product assembly and labour costs (Jelle 2015; Morris 2013; Jelle et al. 2012); ultimately leading to the amortisation of the PV system cost (Heinstein et al. 2013). Environmentally speaking, BIPV lessens the Social Cost of Carbon (SCC) relating to public and environmental health (Yang & Zou 2016) and maximises the pollution-free benefit of solar energy (Jelle et al. 2012).

At present, there is a wide range of BIPV products which harness these benefits and can be categorized in different ways. One way is mainly based on how the manufacturer describes the product and what other type of material the product is customized to be combined with (Jelle 2015; Nikolić et al. 2014; Jelle et al. 2012). However, the PV technology is the basic foundation of these various products. Fig. 1 shows the parts of a PV module used in manufacturing various products.
The product categories considered in this paper are foils or thin film, tiles, modules and solar cell glazing products. The modules can normally be used with various kinds of roofing material. The solar cell glazing products can be integrated in the facade, roof or in fenestration products, e.g. windows, and provide various aesthetic solutions. Table 1 shows the range of classifying and applying BIPV products.

<table>
<thead>
<tr>
<th>TYPE OF PRODUCT</th>
<th>DESCRIPTION</th>
<th>SAMPLE MODULE</th>
<th>BUILDING APPLICATION</th>
</tr>
</thead>
</table>
| BIPV tile       | • Used on the roofs  
• Appears like standard roof tiles  
• Good for retrofitting purposes  | ![BIPV tile](image1.png) | ![BIPV tile](image2.png) |
| BIPV Foil (Thin Film) | • Lightweight, flexible and easy to install.  
• Maintains sufficient efficiency in high temperatures  
• Used on roofs, walls or glazing of varying slopes or curvature. | ![BIPV Foil](image3.png) | ![BIPV Foil](image4.png) |
| BIPV module     | • Similar to conventional PV modules but with weather skin solutions.  
• Used on roofs and walls.  
• Good for retrofitting. | ![BIPV module](image5.png) | ![BIPV module](image6.png) |
| BIPV glazing    | • Multiple uses in windows; glazed or tiled facades and roofs.  
• Different sizes, colours, patterns and transparencies  
• High aesthetic value | ![BIPV glazing](image7.png) | ![BIPV glazing](image8.png) |
3 BIPV-Mass Customisation Index

De Berardinis & Bonomo (2013) suggest that contemporary demand for mass customisation of the building industry requires considering an innovative “craft dimension” of technology to advance the design paradigm of the “micro-intervention” and “controlled transformation”. This ideology is consistent with the aim of developing the BIPV-Mass custom index which is based in part on recommendations of the IEA SHC Task 41 on Solar Energy and Architecture. The standard put forward by the Task 41 Sub-Task A is an overview and description of criteria for architectural integration of photovoltaics -and solar thermal systems, in buildings (Farkas et al., 2013; Munari Probst & Roecker, 2013). The Task highlights PV integration levels as:

- Basic level of integrability: ensuring module formal flexibility.
- Medium level of integrability: providing dummies (i.e. non-active elements).
- Advanced level of integrability: providing a complete roof/façade system.

It also provides an evaluation of integration characteristics being multi-functionality, shape and size flexibility, pattern choice, colour choice, jointing/framing, availability of dummies, complete construction system.

Based on these criteria, this section describes the methodological approach to the development of the graphical index starting with the multi-faceted dimensions of BIPV variables which satisfy some of these integration characteristics and impact its Visual Architectural Impression (VAI), so as to produce a vast number of custom-products. A 2005 research at Concordia University for the Solar Decathlon housing competition installed PV modules as part of a prototype mass custom home. Along with standard features, color options were given to the panels to ensure some custom options for the PV roof modules (Noguchi & Hadjiri 2009). A list of component requirements was used to guide the design and combination of the various components and sub-components presents the potential of customising BIPV products to address the direction of formal aesthetics put forward by the IEA Task 41.

3.1 Requirements and Components

In order to ensure that the Index is able to produce unique prototypes, the following requirements for the development of the Index were selected as a guide:

- Unique Variables: the variables of the Index must be inherently unique or visually different. Variables like geometry, colour and form should be easily identifiable.
- Measurable Performance: the impact of each item on the index should have a measurable rating to ensure that the differences in each run on the Index can be assessed on some logical performance scale.
- Flexibility: both the process of combination and application of the unique output of the Index should be practical and realistic in production and installation.

To create the list of components for the Index, parts of a BIPV module were divided into two (2) categories based on their potential to alter the appearance of the façade i.e the Visual Architectural Impression (VAI); and lead to unique Mass Customisation opportunities. They are:

1. **Design and Fabrication component**: this is the main grouping for the PV cell and module design of the BIPV array. Based on a previous work by De Berardinis & Bonomo (2013), the customizable parts of a BIPV module are the PV Cell, Module Layering and Module features. Table 2 shows the selected division of this component for the index, into four (4) potential sub-components, with a combined total of thirteen (13) 1st level
variables and nine (9) 2nd level variables. An example is the Cell Technology sub-component which has five (5) 1st level variables i.e. mono-Si, poly-Si, a-Si, CIGS and Organic.

2. Architectural Integration component: this encompasses two (2) sub-components based on location and product type. It describes the basic ways of integrating PVs into various locations buildings according to various researchers (Jelle 2015; Munari Probst & Roecker, 2013; Farkas et al. 2013; Heinstein et al. 2013; Montoro et al. & Thomas 2003). These are, on the roof, façade, external devices or advanced systems; and represent the Location sub-component. The Product sub-component used is based on recent reviews (Shukla et al. 2016; Jelle 2015; Nikolić et al. 2014ś Jelle et al. 2012). This component was divided into two (2) potential sub-components, with a combined total of eight (8) 1st level variables and nine (9) 2nd level variables as presented in Table 2 above.

Table 2: Structure of the BIPV-Mass Customisation Index

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>SUB COMPONENT</th>
<th>1ST LEVEL VARIABLE</th>
<th>2ND LEVEL VARIABLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN AND FABRICATION</td>
<td>Cell technology</td>
<td>Mono-Si</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poly-Si</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a-Si</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIGS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Organic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cell shape</td>
<td>Square</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hexagonal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module design</td>
<td>Packing Factor</td>
<td>Option #1: Close</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Option #2: Far</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glass/Sheet Material</td>
<td>Transparent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coloured</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frame Colour</td>
<td>Option #1: Dark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Option #2: Light</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell Arrangement</td>
<td>Option #1: Conventional</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Option #2: Patterns</td>
</tr>
<tr>
<td></td>
<td>Module arrangement</td>
<td>Option #1: Conventional</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Option #2: Unique (Diagonal)</td>
<td></td>
</tr>
<tr>
<td>ARCHITECTURAL INTEGRATION</td>
<td>Location</td>
<td>Roof</td>
<td>Flat</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pitched</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Façade</td>
<td>Curved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Window</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exterior Devices</td>
<td>Option #1: Shading</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Advanced Systems</td>
<td>Double Skin Facade</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sun-Tracking Facades</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Products</td>
<td>Tiles</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Module</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glazing</td>
<td></td>
</tr>
</tbody>
</table>

3.2

3.3 Development of the Index

Based on the above information, the Index was created to guide combinations of variables of the Components and Sub-components and create unique BIPV products. This was accomplished by defining a structural and an operational framework, each one of them detailing the actual information that will be used to customize the BIPV products. While
the structural framework highlights the entire scope of potential options, the operational framework used in this paper is a scaled-down version due to the complexity of possible combinations derived from the structural framework.

3.3.1 Structural Framework
This contains a complete list of components, sub-components and variables selected to define the Index. As technology advances, the flexibility of the list allows for new options to be added to the sub-component or variable columns thus, increasing the number of possible custom products. Table 2 above is the complete Index structure outlining the various possible designs of multiple BIPV product prototypes.

Some items on the Index have multiple 1st level variables that were not included in the framework because they are not a significant part of the current BIPV market. For example, only five (5) cell technology types are mentioned in the structure of the index. Also, some 2nd level variables have theoretically an infinite number of options such as the packing factor, frame colour and cell arrangement. In these cases, only two (2) options with extreme defining visual impressions are selected for clarity and practicality. The present structure has a total of thirty-nine (39) variables; twenty-one (21) on the 1st level and eighteen (18) on the 2nd level.

3.3.2 Operational Framework
The operation of the Index has been divided into two (2) procedural stages based on a logical course; starting from a customisation of the PV module (i.e. the Design and Fabrication component) and then of the BIPV façade (i.e. the Architectural Integration component). The steps taken for this process is shown in Fig. 2 below.

![Figure 2: Operational Framework for the BIPV-Mass Customisation index](image)

This breakdown gives a total of twenty-two (22) variables for the customisation of the PV module and seventeen (17) variables. To reflect the practical application of the operational framework in the Index, a simplified example has been created. For reasons of clarity and expediency the BIPV-Mass Custom Index in Fig. 3 below shows only one (1) 1st level variable leading to the customisation of the PV module.
Figure 3: Screenshots of the BIPV-Mass Customisation index
(BIPV-Mass Custom Index showing a Mono-Si cell with a Square Cell Design, Close Packing factor, Transparent Sheet Materials, Light-coloured frame, Conventional Cell Arrangement and Module Assembly)

Following this process the index produces forty-eight (48) custom options for each of the five (5) sub-components on the index; giving a combined total of two hundred and forty (240) custom PV products for a BIPV façade.

3.4 Evaluation of the Index

The scale below has been proposed as a scale to estimate the performance of the Index based on the set goals (requirements) of the development and its output prototypes.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Visual Architectural Impression (VAI)</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>2 Flexibility</td>
<td></td>
</tr>
<tr>
<td>3 Unique Prototypes</td>
<td></td>
</tr>
<tr>
<td>4 Zero-Energy Potential</td>
<td></td>
</tr>
<tr>
<td>5 Cost</td>
<td></td>
</tr>
<tr>
<td>6 Emission Control</td>
<td></td>
</tr>
<tr>
<td>7 Daylighting</td>
<td></td>
</tr>
<tr>
<td>8 Heating and Cooling</td>
<td></td>
</tr>
</tbody>
</table>

The VAI, Flexibility and Unique prototype parameters have been rated high as each run on the index will fulfill these criteria. Seeing that zero-energy potential, cost, emission control, daylighting and heating and cooling loads, are based on certain parameters unique to each building, like the household energy consumption, it is difficult to estimate these at this time.
4 Conclusion
This paper presents the process of developing a BIPV-Mass Custom Index tool for designers by a combination of multiple variables in the PV design. The results show that the Index is able to produce over two hundred (200) custom PV designs which clients can choose from. The paper presents the first stage of a research to allow for customisation of BIPV products at the point of architectural. While the Index provides multiple options for BIPV manufacturers, it can also guide retrofitting projects with BIPV which have specific visual needs such as colour. It further assists the public to experience the immense potentials of not only the electrical but aesthetic and custom benefits of PV. The strategic impact of the BIPV-Mass Custom index developed reflects architectural, aesthetic and energy efficiency benefits. It presents architects with an easy-to-use tool in BIPV implementation, and can be used as a strategic means of advancing the acceptance of BIPV among building clients. The index further achieves a distinctive integration of renewable options for mass custom housing schemes, leading to multiple advantages and opportunities for future innovation.

Acknowledgements
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PASSIVE DESIGN STRATEGIES TO ACHIEVE LOW-ENERGY AFFORDABLE HOUSING IN CURITIBA

Ke Xu¹ & Masa Noguchi²

¹,² Faculty of Architecture, Building and Planning, The University of Melbourne, Australia
¹ kxu2@student.unimelb.edu.au, ² masa.noguchi@unimelb.edu.au

Abstract: Curitiba, Brazil, is no exception having the urban poverty in Latin American contexts, the improvement of housing energy efficiency for the reduction of utility costs is highly demanded so as to alleviate housing affordability issues arising today. The new definition of affordability is relevant to utility costs and monthly incomes for low-income families. The major challenge of this study is to help these families’ homes to achieve housing affordability through the practice of passive design strategies, which would contribute to raising the energy efficiency and improving the thermal comfort of living environment. The practice in turn contributes to lessening their maintenance costs savings. In this study, appropriate passive design strategies applied especially for Curitiba’s climatic contexts were developed by analysing its local geographical conditions and using an energy performance simulation tool to determine the most effective solution—i.e. the combination of several strategies. The results reflect the effectiveness of passive design strategies set on improving the affordability of utility costs for low-income families between two minimum wages and three minimum wages. This study led to the new definition of operational energy-focused housing affordability, the clarification of performance standards for high energy-efficient housing in Curitiba and a list of appropriate passive design strategies developed as design guidelines for the local architects and builders.

Keywords: Affordability, Housing, Passive Design Strategies, Utility Costs, Energy Efficiency.
1 Introduction
Climate change has adverse effects on people’s life and one of the issues arising today is global warming accelerated by carbon dioxide (CO$_2$) emissions derived partially from unsustainable housing development and operation. Housing sector is one of the major contributors to the CO$_2$ emissions (Du Can et al. 2015). Thus, homes may need to be designed and delivered in a way that helps reduce or eliminate the adverse effects. A sustainable home will be examined in this paper in terms of two major aspects of housing, which encompasses the energy efficiency and affordability. The high level of energy efficiency in housing delivery and operation is one of the major characteristics that contribute to defining sustainable homes. Today, low to zero energy homes and energy plus constructions are increasingly discussed (Rodriguez-Ubinas et al. 2014). Space heating and cooling in housing help the users to secure their thermally comfortable indoor environment, yet they tend to affect the total operational energy consumption drastically (Wagner 2014). Therefore, building passive design strategies for energy efficiency may play a significant role in reducing the energy consumption, when applied properly to the design.

ZEMCH is an acronym of zero energy mass custom homes that reflect social, economic and environmental sustainability in housing (Noguchi 2016). The ZEMCH Workshop was held in Curitiba, Brazil, from 28th March to 1st April 2016 with the aim of delivering low-cost sustainable homes for families of different socio-economic backgrounds. Urban poverty remains a major issue in Curitiba today and it is becoming worse as both population growth and housing price are increasing (Macedo 2013). It is estimated that 10% to 15% population in Curitiba is living in houses operated under the substandard conditions which do not meet the basic requirement regarding safety and sanitary systems (Macedo 2013). Although Curitiba has a housing assistance program called “Cohab-CT” linked to the federal government of Brazil, it focuses on families that earn at least three or more minimum wages per month where one minimum wage is estimated at R$880 (Hayles and Dean 2015). A large amount of households in Curitiba still fall into low-income families who earn less than three minimum wages; therefore, they are not eligible for acquisition of adequate housing. This paper aims to deal with housing affordability of these families in consideration of the operational energy cost.

Building passive strategies encompass an effective energy efficient design approach to reducing the operational energy consumption through the choice of proper orientation, configuration and materials relevant to local climate (Schnieders et al. 2015). However, there are a number of passive design solutions (Brunsgaard et al. 2014). In addition, housing usage patterns affected through user behaviour also has an impact on the energy consumption (Figueiredo et al. 2016).

In this study, passive design strategies applicable to low cost housing development in Curitiba, Brazil, were first identified in consideration of local climate, cultural preferences, and economic capacity. Second, some strategies were selected for further analysis of the effect on housing energy efficiency. At last, the housing affordability was assessed in terms of the percentage of operational energy costs compared to the households’ total monthly incomes. This analysis was conducted by making use of HOT2000, a steady-state energy simulation tool developed by Natural Resources Canada. The following section identifies the definition of affordable housing in view of housing energy costs in Curitiba.
2 Definition of affordable housing in terms of utility cost in Curitiba

Low-income families in Curitiba are suffering extraordinary poverty, and by specially considering utility costs of a home, they pay a much higher proportion of their incomes for these energy services rather than high-income households. It leads to a worse situation of the low-income families’ living conditions, which cannot be improved by affordable housing strategy currently as the current definition of affordable housing has a lack of focus on operational costs of a house. Therefore, a new definition of affordable housing should be identified for the purpose of improving the situation of people’s livelihood, especially for low-income families. In particular, the two focuses of this new definition are low-income families in Curitiba and utility costs they spend on operating a home.

Additionally, low-income families are defined as a family earning the equivalent incomes lower than three Minimum Salaries monthly. One Minimal Salary (MS) is equal to 880 Brazilian Real in 2006, which means low-income families earn less than $R2640 per month (Macedo 2013). Hence, 3MS is considered as the turning point between low-income families to middle-class families, and the relevant percentage of monthly expense on utility cost by the households who earn 3MS is the changing point between unaffordable operating cost and affordable operating cost (Moore 2007). So, this critical percentage is the key evaluated point for the new definition of affordability. However, the value of this percentage cannot be used directly for the new definition, which should be validated according the energy simulation tool. Then, the modified percentage will be used to define affordable housing in terms of utility costs.

2.1 Breakdown of Monthly Utility Costs and Their Percentages on Monthly Incomes in Curitiba

The first step is finding the existing data in Curitiba about the percentages of current utility costs for each class income families (Fig.1). MS is the unit of monthly minimum wage and in 2016 1MS=$880. In addition, 80% of residential energy is consumed by mainly low-income families (lower than 3MS). The poorest strata of the population (below 1MS) is paying the highest portion (6.2%) of their income for utility cost or energy services, while the richest people who earn over 20MS is only spending 0.7% of their incomes for the energy costs (Borgstein and Lamberts 2014). Importantly, the first middle class families are regarded as the group of people whose incomes are just more than 3MS, and they are spending around 3.70% incomes on energy services (Borgstein and Lamberts 2014). So, based on the analysis above, the critical percentage for the existing condition of utility costs is 3.70% as it is the turning point between low-income families and middle-class households.

![Figure 1: Percentage of monthly expense on utility costs in reality](image)
However, this percentage should be validated and modified for the new definition of affordability by the energy simulation tool (HOT 2000). For a typical family energy consumption breakdown in Curitiba, there are three major energy consumptions including hot water (24%), cooling (20%) and electrical devices (56%) (Fig.2). In particular, electrical devices are comprised with refrigerator (22%), lamps (14%), televisions (9%), freezers (5%), iron (3%) and sound (3%) (Borgstein and Lamberts 2014). It is quite obvious from this pie chart (Fig.2) that no energy is used for heating. In Curitiba, traditionally people do not use any heating facilities during the winter and so there is not heating section in the energy consumption breakdown chart. However, when using the weather data of Curitiba to run the HOT2000, it suggests there are around 27% energy used for heating (Fig.3). This contradiction might because heating is necessary in the winter of Curitiba, but people are already used to the condition without heaters. Hence, for this study, it uses HOT2000 as a tool for the following analysis, a new energy consumption breakdown will be created by considering the existing energy consumption distribution and adding the heating energy consumption into the pie chart as well. In Addition, the critical modified percentage for utility costs of low-income families will be calculated based on the new energy consumption breakdown.

Figure 2: Breakdown of energy consumption of existing house in Curitiba

2.2 Energy Performance Simulation of Existing House for The Definition

By using energy simulation tool HOT2000, heating loads and air conditioners are necessary for the existing house conditions in order to provide appropriate thermal comfort for occupants. The major modification for the energy consumption breakdown will be made by adding heating energy consumption by modelling the existing house conditions. It illustrates all criteria used in HOT2000 about the existing house conditions based on reality of Curitiba social housing, which is set as benchmark for the following research (Tab.1). A new pie chart of energy consumption is created according to modelling results (Fig. 3). It is made up of four major categories: heating (27%), cooling (14%), hot water (17%) and electrical devices (42%). More important, the relevant percentages of monthly expense on utility are changed as well, based on the new breakdown of energy consumption. So, the modified critical percentage for the affordability by only considering utility costs is set as 5.54% (Fig. 4).
Table 6: HOT2000 criteria for the existing house

<table>
<thead>
<tr>
<th>HOT2000 Criteria</th>
<th>Existing House Conditions</th>
</tr>
</thead>
</table>
| House specifications | Dimension of the house: 6m×5.8m;  
Wall height 2.8m; door size: 0.8m×2.1m.  
House type: Single Unit  
Storeys: One storey  
Plan shape: Rectangular  
Front orientation: Northeast  
Wall Colour: Light green; value 0.47  
Roof Colour: Medium Brown; value: 0.84  
Foundation Soil Condition: Normal conductivity  
Water table level: Normal |
| Thermal Mass | Heavy, masonry;  
Effective Mass Fraction: 1.00  
Walls: double bricks  
Floors: solid concrete block  
Ceilings: solid concrete block |
| Airtightness | Window Air Tightness is CSA-A1, 2.79 m3/h/m;  
Leakage Fraction for ceilings, walls  
And floors are 1, 1 and 1.  
Airtightness type: Loose (10.35ACH@50Pa) |
| Insulation | No insulation for walls, windows, ceilings and floors |
| Windows | Two windows on the northeast and  
Southwest walls with 1m × 1m dimension  
No shading for windows |
| Temperatures | Heating set point 21 degrees  
Cooling set point 25 degrees |
| Heating and Cooling | Baseboards  
Air conditioning |
| Base Loads | Assume all using electricity  
2 adults and 2 children with 50% time at home  
7 kWh/day for average interior loads  
135L/day for hot water load, temperature set at 55 degrees  
Number of low flush toilets 10 times |
| DHW | Electricity |

Energy consumption breakdown in modelling

Figure 3: Modelling energy consumption of existing house with heating
Based on the analysis above, the new definition of affordability is identified as a household spends less than 5.54% of their monthly incomes for energy services of a house, and this house will be regarded as affordable. So, for this definition, it is obvious that low-income families are all living in unaffordable housing. In addition, this definition is the fundamental criterion of this research. The main purpose of the research is going to develop appropriate passive design strategies to improve energy performance of low-income homes, aiming to reducing energy consumption to achieve less 5.54% of their monthly incomes spent on energy services. So, spending less than the modified critical percentage (5.54%) for energy services of a home is set as a final goal. The evaluation for whether these strategies are successful or not will depend on whether the improved house equipped with a bunch of passive strategies consumes less energy to achieve the goal. However, implementing these passive design strategies to a house might lead to an increase of initial costs, which is a major concern for low-income families. So, it is necessary to find capital subsidy from the government and other relevant departments. Although it is not the significance of this paper, two suggestions will be given for an insight. For example, additional cost could be covered by the social housing programs, which is organized by the government (Scalco et al. 2012). Additionally, energy performance contracting with an energy service company (ESCO) or with the power utility could be another way for energy demands management (Bodach and Hamhaber 2010). The ESCO could cover all projects cost over a contract term of up to ten years through energy savings. Hence, the initial cost for proposed passive strategies could be neglected as it is not necessary covered by low-income families themselves.

The following sections are organized for selecting appropriate passive design strategies and evaluating these strategies by using HOT2000 and the definition of affordability identified above.

3 Creating Energy Performance Standards for Curitiba

The main objective of this paper is going to develop appropriate passive design strategies for low-income families in Curitiba. In an attempt to minimize energy consumption in residential sector, there are some international and national standards for evaluating
housing energy efficiency. The two standards are considered for this research, including Brazilian Labelling Scheme Labelling Scheme for Residential Buildings (RTQ-R label) and the Passivhaus Standard which was developed in Germany but widely used in the world (Tubelo et al. 2014). However, these two standards are all catering for a large scale area, which might be ineffective for Curitiba. So, in this research, it is necessary to create local energy efficiency standards for Curitiba based on these two universal standards, by special considering economic capacities of low-income families and the local climate. After identifying strengths and constrains of these two standards, and also analysing the local climate conditions above, Curitiba standards for energy efficient homes is developed (Tab.2). It provides guidelines for developing appropriate passive design strategies in the next section.

<table>
<thead>
<tr>
<th>Standard Requirement</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard requirements</td>
<td></td>
</tr>
<tr>
<td>Primary energy demand</td>
<td>≤120 KWh/m2a</td>
</tr>
<tr>
<td>Heating or cooling demand</td>
<td>≤15 KWh/m2a</td>
</tr>
<tr>
<td>Heating or cooling load</td>
<td>≤10 W/m2</td>
</tr>
<tr>
<td>Indoor comfort design parameters</td>
<td></td>
</tr>
<tr>
<td>Comfort temperature</td>
<td>20 °C &lt; T &lt; 24 °C</td>
</tr>
<tr>
<td>Typical design solution</td>
<td></td>
</tr>
<tr>
<td>Airtightness</td>
<td>n50 (h-1) ≤ 0.6, at 50 Pa,</td>
</tr>
<tr>
<td>U-value wall</td>
<td>≤2.5 W/m2K</td>
</tr>
<tr>
<td>U-value roof</td>
<td>≤3 W/m2K</td>
</tr>
<tr>
<td>U-value glazing</td>
<td>≤0.8 W/m2K</td>
</tr>
<tr>
<td>Opaque elements</td>
<td>0.3-0.4 W/m2K</td>
</tr>
<tr>
<td>Natural Ventilation</td>
<td>operable windows Ceiling fans</td>
</tr>
<tr>
<td>Windows</td>
<td>≥8% for floor area</td>
</tr>
<tr>
<td></td>
<td>Double glazing sun protection</td>
</tr>
</tbody>
</table>

4 Passive Design Strategies

There are already numerous passive strategies adopted around the world successfully, but the key challenge for this paper is to finding out suitable strategies for low-income families in Curitiba. It not only needs to consider the local climate of Curitiba but also economic capacities of low-income families. Additionally, proposed passive strategies for Curitiba will be developed by focusing on passive solar heating and passive cooling, which are two significant parts of energy efficient houses. Then special design principles will be developed aiming to reducing heating and cooling of the existing home of Curitiba. Finally, these principles will be assessed in HOT2000, through converting them into relevant criteria of the software, and then evaluating the result of energy performance when the relevant criteria are changed.

4.1 Passive Solar Heating

Passive solar heating is the least expensive way to save energy and improve thermal comfort of houses. Since heating is predominant in Curitiba (27% of total energy consumption by modelling), passive heating could gain heat during the winter and allow heat escape in summer, which aims to reduce heating energy use to zero. There are several elements contributing to passive heating. Building envelope is the most important feature of the building since it constitutes the limit between interior and exterior conditions (Burman et al. 2014). In addition, improving thermal performance of building envelope is
one of the most effective ways to minimize the energy consumption in terms of interior thermal comfort. The thermal transmittance (U value) is the most relevant indicator to be considered for building envelope and there are some other considerations as well for the building envelope (Copiello 2015). In particular, insulation, thermal mass, airtightness, windows and shading are all relevant to envelope, while some other criteria such as orientation should be also considered.

4.2 Passive Cooling
Passive cooling strategies are other essential contributors for reducing cooling energy demand, which is 14% of total energy consumption by modelling. Passive cooling is more difficult in Curitiba than other weather conditions because of the humidity (higher than 60%). So, it needs strong ventilation system to decrease humidity and reduce temperature. This new system could be cross ventilation with big window openings combined with mechanical fans to enhance air movement (Copiello 2015). Although fans use energy, which could be also regarded as a passive strategy due to the energy use is greatly less than air conditioners (Schnieders et al. 2015). The same as passive heating, there are same elements considered for passive cooling, such as insulation, thermal mass, position and glazing of windows and shading.

4.3 Deign Principles
The following sector will describe each criteria or principles regarding passive heating and cooling.

4.3.1 Insulation
Insulation is a barrier to heat flow and it is essential for keeping the house for year-round comfort, which means it can keep the house warm in the winter and cool in the summer. Appropriate insulation will reduce energy consumption up to 50% and it should cater for the seasonal and daily variations in temperature (Mosher and McGee 2013). Furthermore, the well-designed insulation should also be combined with other passive design strategies, such as shading, to get optimal outcomes. According to the climate analysis, the minimal insulation level (Total R-value) for Curitiba should be 4.1 for roof and ceiling, while 2.8 for walls.

4.3.2 Airtightness
Envelope airtightness is the fundamental building property that impact infiltration, including uncontrolled air leakage from outdoor air and unintentional openings of a house, which is caused by different pressure around the building envelope and the effect of external wind (Reardon 2013).

Tight building envelope will significantly reduce the heat loss, which leads to a reduction of heating and cooling capacities. So, house sealing is the easiest and the most cost saving way to against air leakage but improve thermal comfort while reducing the energy bills. More specifically, the air leakage value \( n_{50} \) should be smaller than 0.6 h\(^{-1}\) to maintain the thermal comfort for habitat areas. Therefore, providing seals to openings to minimise unwanted draughts could be significant for reducing energy cost.

4.3.3 Windows
Windows are complex elements with multifunction in terms of building fabric. They not only allow natural lights and fresh air letting in, but they could also be the major source of heat loss in winter and heat gain in summer. Hence, energy efficient windows with appropriate glazing strategies and shading solutions are highly recommended to improve thermal
performance of the house, since 87% of heat gain and up to 40% of heat loss through windows (Schnieders et al. 2015).

In Curitiba, the opaque elements and the glazing surfaces should have a compatible level of resistance to avoid the solar radiation heat to enter the building during the cooling season and to allow the solar radiation heat to enter the building during the heating season. In particular, the cost-optimal glazing with consideration of heating and cooling should be double-glazing windows with sun protection, and the U value for glazing should be smaller than 0.8 W/m²K. Meanwhile, the recommended U-value for the opaque elements of the building is between 0.3 W/m²K to 0.4 W/m²K (Bodach and Hammababer 2010).

In some other places, windows may not need to be used for ventilation; however, natural ventilation is used extensively in Brazil. According to the bioclimatic of zone of Curitiba, cross ventilation is highly recommended and the opening areas for ventilation should be between 8% -10% of the floor area.

4.3.4 Shading
Shading devices could vary and they should be designated according to building orientation and climate conditions. Since effective shading could block up to 90% direct solar heat, appropriate shading devices could reduce summer temperature and improve thermal comfort (McGee 2013). Windows with shading are necessary in Curitiba and all north-facing openings should be shaded well with correctly sized eaves for this warm humid climate. Meanwhile, in terms of east and west, adjustable screens or deep overhangs are suggested as they can prevent low angel sun effectively. More importantly, well-designed eaves are the easiest and cheapest shading solutions for northern elevations and single-level houses.

4.3.5 Thermal Mass
Thermal mass is the ability of materials such as concrete, brick or timber to absorb and store heat energy and the appropriate use of thermal mass will make a big difference about thermal comfort in the house (Reardon et al. 2013). In addition, selecting correct thermal mass materials should base on the range of daily temperature and the daily temperature range in Curitiba is about 10 °C to 11°C, which is suitable for high mass construction. Since the existing condition of the house in Curitiba is built by double brick, which is high thermal mass materials.

5 Energy performance Modelling
Several design principles are identified above and the key principles are summarised as thermal mass, airtightness, insulation and windows. In terms of each principle, many criteria of HOT2000 are descripted and they will be used for modelling (Tab.3).
Table 8: Basic passive design principle descriptions

<table>
<thead>
<tr>
<th>Number</th>
<th>Principles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Low Thermal Mass</td>
<td>Light Wood frame, structure and components for walls, ceilings and floors</td>
</tr>
<tr>
<td>1B</td>
<td>Airtightness</td>
<td>Window Air Tightness is CSA-A3, 0.55 m3/h/m; Leakage Fractions for ceilings, walls and floors are 0.5 Air Tightness Type: Energy tight (1.5ACH@50Pa)</td>
</tr>
<tr>
<td>1C</td>
<td>Insulation</td>
<td>Insulation for all walls, ceilings and floors Insulation Layer 1: RSI 1.7 (R10) Batt Insulation Layer 2: 13mm (0.5 in) EPS I Interior: 12 mm gypsum board Sheathing: Waterboard/OSB 9.5mm Exterior: Stucco</td>
</tr>
<tr>
<td>1D</td>
<td>Windows</td>
<td>Add one window each on the east and west walls, with dimension of 1m × 1m; Increase the size of windows on the south and north walls from 1 m2 to 4 m2; Adding shading to the windows with overhang width 0.8m and header height 2.3m for windows on south and north side Adding shading to the windows with overhang width 0.3m and header height 1.3m for windows on east and west side All windows are insulated and double glazed: Glazing type: double with 1 coat (excepted the north window is clear) Coatings: Low-E 0.04 soft Fill type: 6 mm Air Spacer Type: Insulating Window type: Slider with sash Frame material: Wood frame</td>
</tr>
<tr>
<td>2B+Fan</td>
<td>Airtightness and Insulation with Ceiling Fans</td>
<td>Indoor Fan flow rate: 180L/s Power: 140 W No Air conditioning</td>
</tr>
</tbody>
</table>

5.1 Passive Solutions

Since passive design strategies could be more effective by appropriated combinations of different principles. Therefore, every two, three and four principles will be combined together as new strategy packages to see the effectiveness of their combinations. So, based on the basic four principles (1A, 1B, 1C and 1D), it is developed into sixteen strategies. The following list is the strategy packages and the relevant number, which will be used for the final result analysis (Tab.4). Every strategy will be run in HOT 2000 to see the annual energy consumption by devices, including space heating, Domestic Hot Water (DWH) heating, Lights and Appliances, Fans and Air Conditioners. Then it will calculate the total annual energy consumption for all purposes and compare it with the energy use of existing house to calculate energy consumption change by percentage. Positive value of the percentage means energy consumption is increasing through implementing the relevant strategy, while negative value shows a reduction of energy uses, which is what we are looking for. In terms of the calculation of changed percentages, it bases on electricity fee (0.76683 R$/KWh) in Curitiba and monthly incomes of low-income families with 1 minimum salary (R$ 880), 2 minimum salaries (R$ 1760), and 3 minimum salaries (R$ 2640) respectively. The existing house with its HOT2000 criteria are already identified (Tab.1), and the basic energy consumption is determined, which is 190.85 KWh/month (Tab.5). Then, it is going to determine new energy consumption with each strategy implemented. Finally, calculating how many percentages the new energy consumptions is consisting to monthly incomes of 1MS, 2MS and 3MS families, respectively. So, these percentages are critical values to evaluate the level of affordability of a house implemented.
with relevant passive design strategies. The benchmark is 5.54% identified before. The detailed analysis will be described in section 6.2.

Table 9: The number of passive design strategy packages (solutions)

<table>
<thead>
<tr>
<th>Number</th>
<th>Strategy Packages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>Existing House</td>
</tr>
<tr>
<td>1A</td>
<td>Low Thermal Mass</td>
</tr>
<tr>
<td>1B</td>
<td>Airtightness</td>
</tr>
<tr>
<td>1C</td>
<td>Insulation</td>
</tr>
<tr>
<td>1D</td>
<td>Windows</td>
</tr>
<tr>
<td>2A</td>
<td>Low thermal mass and Insulation</td>
</tr>
<tr>
<td>2B</td>
<td>Airtightness and Insulation</td>
</tr>
<tr>
<td>2C</td>
<td>Windows and Insulation</td>
</tr>
<tr>
<td>2D</td>
<td>Low thermal mass and Airtightness</td>
</tr>
<tr>
<td>2E</td>
<td>Airtightness and Windows</td>
</tr>
<tr>
<td>2F</td>
<td>Thermal mass and Windows</td>
</tr>
<tr>
<td>3A</td>
<td>Low thermal mass, Airtightness and Insulation</td>
</tr>
<tr>
<td>3B</td>
<td>Low thermal mass, Airtightness and Windows</td>
</tr>
<tr>
<td>3C</td>
<td>Thermal mass, Insulation and Windows</td>
</tr>
<tr>
<td>3D</td>
<td>Airtightness, window and insulation</td>
</tr>
<tr>
<td>4A</td>
<td>Thermal mass, airtightness, insulation and windows</td>
</tr>
<tr>
<td>2B+Fan</td>
<td>Airtightness and Insulation with Ceiling Fans</td>
</tr>
</tbody>
</table>

5.2 Results Analysis and Discussion

The modelling results for all the strategy packages are compared and listed mainly depending on the achieved percentages of utility costs out of each levels' incomes (Tab.5). There are 16 strategy packages in total and they will be ranked according to energy reduction. The first place is the most effective passive design strategies with the most energy reduction. This package might be the most appropriate passive strategies for low-income families in Curitiba, which improves the highest level of affordability for low-income families to operate a house. Some other significant findings are concluded based on this analysis table in the following section.

Table 10: Final result analysis of passive design solutions

<table>
<thead>
<tr>
<th>Number</th>
<th>kWh/month</th>
<th>Energy change %</th>
<th>R$ 880</th>
<th>1MS 1760</th>
<th>2MS 5280</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>190.85</td>
<td>0</td>
<td>146.26</td>
<td>16.62%</td>
<td>8.31%</td>
<td>13</td>
</tr>
<tr>
<td>1A</td>
<td>234.62</td>
<td>22.93%</td>
<td>179.81</td>
<td>20.43%</td>
<td>10.22%</td>
<td>6.81%</td>
</tr>
<tr>
<td>1B</td>
<td>185.82</td>
<td>-2.64%</td>
<td>142.41</td>
<td>16.18%</td>
<td>8.09%</td>
<td>5.39%</td>
</tr>
<tr>
<td>1C</td>
<td>133.75</td>
<td>-29.92%</td>
<td>102.50</td>
<td>11.65%</td>
<td>5.82%</td>
<td>3.88%</td>
</tr>
<tr>
<td>1D</td>
<td>185.40</td>
<td>-2.86%</td>
<td>142.09</td>
<td>16.15%</td>
<td>8.07%</td>
<td>5.38%</td>
</tr>
<tr>
<td>2A</td>
<td>134.76</td>
<td>-29.39%</td>
<td>103.28</td>
<td>11.74%</td>
<td>5.81%</td>
<td>3.87%</td>
</tr>
<tr>
<td>2B</td>
<td>133.37</td>
<td>-30.12%</td>
<td>102.21</td>
<td>11.62%</td>
<td>5.81%</td>
<td>3.87%</td>
</tr>
<tr>
<td>2C</td>
<td>139.54</td>
<td>-26.88%</td>
<td>106.94</td>
<td>12.15%</td>
<td>6.08%</td>
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</tr>
<tr>
<td>2D</td>
<td>103.79</td>
<td>20.19%</td>
<td>175.80</td>
<td>19.98%</td>
<td>9.99%</td>
<td>6.66%</td>
</tr>
<tr>
<td>2E</td>
<td>183.99</td>
<td>-3.59%</td>
<td>141.01</td>
<td>16.02%</td>
<td>8.01%</td>
<td>5.34%</td>
</tr>
<tr>
<td>2F</td>
<td>222.27</td>
<td>16.46%</td>
<td>170.34</td>
<td>19.36%</td>
<td>9.68%</td>
<td>6.45%</td>
</tr>
<tr>
<td>3A</td>
<td>134.42</td>
<td>-29.57%</td>
<td>103.02</td>
<td>11.71%</td>
<td>5.85%</td>
<td>3.90%</td>
</tr>
<tr>
<td>3B</td>
<td>230.10</td>
<td>20.57%</td>
<td>176.34</td>
<td>20.04%</td>
<td>10.02%</td>
<td>6.68%</td>
</tr>
<tr>
<td>3C</td>
<td>141.90</td>
<td>-25.65%</td>
<td>108.75</td>
<td>12.36%</td>
<td>6.18%</td>
<td>4.12%</td>
</tr>
<tr>
<td>3D</td>
<td>133.08</td>
<td>-30.27%</td>
<td>101.99</td>
<td>11.59%</td>
<td>5.79%</td>
<td>3.86%</td>
</tr>
<tr>
<td>4A</td>
<td>144.65</td>
<td>-24.21%</td>
<td>110.86</td>
<td>12.60%</td>
<td>6.30%</td>
<td>4.20%</td>
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<tr>
<td>3D+Fan</td>
<td>116.90</td>
<td>-38.75%</td>
<td>89.58982</td>
<td>10.18%</td>
<td>5.09%</td>
<td>3.39%</td>
</tr>
</tbody>
</table>
5.2.1 Single Category: (1A-1D)
- Insulation is the most effective solution for energy reduction, which could reduce energy consumption by 29.92%. It is ranked 3rd place.
- Airtightness and windows could contribute 2.64% and 2.86% of energy reductions, which is not significant but necessary.
- Low thermal mass is not a desirable construction material for Curitiba, which results in increasing 2.93% energy consumption.

5.2.2 Two Categories: (2A-2F)
- Solution 2B (Airtightness and insulation) ranked in 3rd place, which is the 2nd most effective strategy package without considering ceiling fans. It could reduce space heating energy to zero. All these two categories including airtightness and insulation aim to tight the building and reduce heat loss.
- The effect of insulation overwhelms the effect of low thermal mass, as the result of solution 2A shows an energy reduction (29.39%) by combining these two strategies. It is to say that low thermal mass could become effective for lower energy requirement with good insulation. However, it still has negative effect on energy reduction with only window solutions or airtightness.

5.2.3 Three and four Categories: (2A-2F and 4A)
- Solution 3D is supposed to be the most effective strategy package, since it is the combination of all effective strategies involving airtightness, windows and insulation. The simulation result demonstrated that Solution 3D reduced energy by 30.27%, which is ranked 2nd place without using fans. Therefore, it can be seen that the effectiveness of the combination strategies could be accumulated by each strategy if they are all appropriate and correct strategies. However, the final performance should still base on simulation results.

5.2.4 3D+Fan—Optimal solution
- This is the most effective solution for saving energy, with 34.87% energy reduction. It is determined based on the 2nd best solution 3D and it adds ceiling fans to reduce cooling need. Solution 2B has already reduced heating energy to zero, and it is necessary to reduce cooling demand to achieve affordability. Big opening windows are designed for better cross ventilation and adding ceiling fans also aims to increasing air movement in order to reduce air conditioner demand. Finally, this solution could reduce heating energy to zero and reduce cooling energy as much as possible by removing air conditioner.
- The housing living by people who earn 2MS to 3MS can become affordable housing through using this solution, since the utility cost makes up only 5.09% of total incomes, which is smaller than affordability level 5.54%. This is the main contribution of this paper.
- Furthermore, it found that the improvement of windows is not as effective as the use of fans, and reinforce the importance of a well isolated fabric for the thermal envelope, which indicated that low thermal masses are inapplicable in Curitiba.
- However, the house with the most effective passive design strategies is still not affordable for people who earn less than 2MS, and the major reason for that is they are extremely poor. On the other hand, although the passive design strategies cannot help these people to reach affordable level, it still helps them to reduce the energy costs by around 5% from (16.62% to 10.18%). It probably saves a significant amount of money for these extremely poor people.
6 Conclusions
In Curitiba, urban poverty is still a crucial issue for local residents and one main reason for this is that they cannot live in a proper house. For low-income families, high operating fees for energy services prevent them from living in a healthy and thermally comfortable condition. This is because that the existing social houses has very low energy efficiency, which results in high utility costs and unaffordability for low-income families. However, the common definition of housing affordability neglects operating costs of a house, which is the major concern for low-income families. So, defining housing affordability by focusing on utility costs is the first main objective of this paper. The affordability is identified as a household spends less than 5.54% of their monthly incomes for energy services of a house. The second main objective of this paper is to reduce the utility costs for low-income families to the defined affordable level by a list of appropriate passive design strategies. It is because that passive design strategies are recognized as the most effective and cheapest way to improve energy performance of a house, leading to a significant reduction of energy consumption (Altan et al. 2015).

There are three major contributions of this paper, including a new definition of affordability, local standards for Curitiba Social Housing and a list of appropriate Passive Design Strategies. Based on the new definition of affordability, the most effective passive design strategy is identified as 3D+Fan solution, and it can change part of low-income families who earn 2MS to 3MS to achieve affordable level with 5.09% of monthly expense on utility costs. However, the house with this strategy (3D+Fan) is still not affordable for people who earn less than 2MS, and the major reason for that is the extreme poverty and the limitation of passive design strategies for energy savings.

References


THERMAL PERFORMANCE OF PLANT-SHADED BUILDING FAÇADES IN HOT CLIMATE

Mahmoud Haggag¹ & Ahmed Hassan²

¹,² Arch. Eng. Department, College of Engineering, UAEU, UAE, ¹ Ahmed.Hassan@uaeu.ac.ae, ² mhaggag@uaeu.ac.ae

Abstract: The hot climate in the United Arab Emirates generates unique challenges to building engineers seeking energy efficient building designs. Design features can influence the indoor environment and reduce energy consumption, including thermal insulation, window size, and glazing types. Additionally, shading effects caused by external plantation can affect the thermal performance of the building façades. The use of intensive plantation around buildings has increased in popularity due to its contribution towards reducing the heat gain. Additionally, plant-shaded wall technique helps in lowering the heat-island effect in the urban context. Plant-shading of building façades is common technique to decrease wall surface as well as inner space temperatures through decreased heat gain due to incident radiations being blocked by the vegetation; evaporative cooling caused by the irrigation water; and heat resistance due to lower thermal conductivity of the plants acting as heat insulators. This paper investigates the potential improvements in the building performance when integrating plant-shaded design strategies into sustainable residential buildings in hot climate. The study examines the thermal performance of plant-shaded façade to reduce cooling load as a strategy of lowering energy consumption. Experimental work was carried out to analyze the impact of using plantation for solar control of residential building façades. External and internal wall surface and ambient temperatures were measured for plant-shaded and bare walls located in Al-Ain during a hot summer period. A literature review was carried out to identify typical design strategy applied to the case study; the use of vegetation and plant-shading techniques was investigated; and thermal insulation effect of plant-shaded wall was tested. The study concluded that shading effect of the intensive plantation has a substantial impact on the thermal performance of residential buildings and can reduce peak time indoor air temperature by 5 °C and reduce the peak air conditioning energy demand by 18%.

Keywords: Al-Ain City, Plant-Shaded Wall, Hot Climate, Thermal Performance, Cooling Load.
1 Introduction: Thermal Performance of Building Skin

Building skin is a major element in determining the amount of energy used in buildings. Skin design should be integrated with other aspects including material selection, daylight, heating, ventilation, and air-conditioning. The opening form and glazing systems have a great impact on energy efficiency of the skin. In hot and arid climates, such as those in Al-Ain city in the Emirate of Abu Dhabi, United Arab Emirates (UAE), the main building design strategy is to control heat gain and allow reasonable visible light transmittance for views and daylight. In cold climates, the strategy is to reduce heat loss and allow desirable solar radiation to enter the space (Straube & Straaten 2001). Construction details and façade systems also play an important role in designing building skin. Appropriate detailing systems are essential to guarantee the required level of thermal performance, which occurs in three ways: conduction, convection, and radiation. Conduction is where heat passes through a building skin. The conductance of particular building materials or construction elements is the amount of heat that will be conducted through a unit area in unit time for unit temperature differences between the faces of building skin (thermal transmission coefficient U-value); the lower the U-value, the better the insulation. In convection process, air flows collect heat from warmer surfaces and convey it to cooler ones. Radiation involves energy transfer by electromagnetic waves (Reid 2001).

Construction engineers can reduce building skin related energy losses by reducing air leakage through the external skin, using high performance windows, increasing insulation layers, and minimizing thermal bridging.

The opening form, size and location have significant impacts on the thermal performance of the building skin. Glazing systems have a great impact on energy efficiency. In hot and arid climates, such as those in Al-Ain city in the Emirate of Abu Dhabi, United Arab Emirates (UAE), the main building design strategy is to control heat gain and allow reasonable visible light transmittance for views and daylight. In cold climates, the strategy is to reduce heat loss and allow desirable solar radiation to enter the space (Straube & Straaten 2001). Construction details and materials of the building skin also play an important role to guarantee the required level of thermal performance, which has to do with reducing thermal transmission coefficient (U-value); the lower the U-value, the better the insulation.

In terms of energy efficiency, the use of vegetation and green wall strategies has gained increasing popularity to minimize heat gain since it can reduce peak time indoor air temperature by 5-7°C and the peak air conditioning energy consumption by about 20% (Haggag, Hassan and Elmasry 2014). Plants can be considered as a solar barrier and absorb a significant amount of solar radiation. The decreased temperature on the green surfaces on building skins can be achieved by decreased heat gain caused by the plantation; the evaporative cooling caused by the irrigation water; and heat resistance due to low thermal conductivity of the plants acting as heat insulators. This concept can increase comfort, reduce operation costs, reduce overall energy consumption and minimize negative environmental impacts. It also contributes directly to LEED credits since it covers issues like sustainability, energy saving, air quality, and sound reduction.

2 Thermal Performance of Vegetated and Plant-shaded Walls

The use of vegetation on and around the building façades can improve thermal performance of building skin. Moreover, vegetated and plant-shaded wall techniques can adjust the urban microclimate and reduce urban heat island effect. Plant-covering and plant-shading of building façades are common techniques to decrease wall surface as well as inner space temperatures through: a) decreased heat gain due to incident radiations
being blocked by the vegetation leaves b) evaporative cooling caused by the irrigation water; and c) heat resistance due to lower thermal conductivity of the plants acting as heat insulators. These techniques can reduce the peak time indoor air temperature and the peak air conditioning energy demand. Moreover plant-shaded surfaces reduce wind effect and help control the humidity within the building zone (Axarli & Eumorfopoulou 2002).

A vegetated wall is used as a term for both green façades and living walls. Green façades are made up of climbing plants that growing directly on a wall or supporting structure. The plant grows up along the wall while being rooted to the ground, in intermediate planters or on the rooftops. Rigid panels and cable systems can be used to hold vines off the wall surface. Living walls are composed of pre-vegetated panels or integrated fabric systems that are fixed vertically to a structural wall or frame (Caplow et al 2008). The popular living wall systems are: Modular Living Walls; Vegetated Mat walls; and Landscape walls (Kontoleon & Eumorfopoulou 2010, Perini et al 2011, Timur & Karaca 2013)

Plant-shaded wall is a passive technique for shading the building façade and reducing solar radiation, wind and precipitation. Trees and vegetation provide shade wherever it is beneficially required. In hot climate, plants and trees facing building Façade do not only reduce the effect of high solar radiation but also the air temperature through the evaporation process caused by irrigation system. Plant-shaded walls can act as vegetated green walls in terms of heat gain reduction and lowering the external and internal wall surface and inner-space temperatures. A plant-shaded wall is a method of passive temperature control that results in reduction of air conditioning load (Kontoleon & Eumorfopoulou 2010).

The level of thermal influence of the plantation depends on several parameters including the covering percentage, density and the width of plant foliage that covers building surfaces and the type and size of the trees surrounding the buildings. Other parameters such as the solar absorption coefficient of exposed surfaces; the specification of external building materials; and the color of the external surface have significant effect on the temperature profiles of the building skin. The thermal impact of the plant foliage depends usually on the orientation of the plant-shaded walls (Kontoleon & Eumorfopoulou 2008). The contribution of thermal insulation within the construction of building skin has also a significant impact on the thermal behavior of the wall even when a plant-covered layer is considered (Kontoleon & Eumorfopoulou 2010).

Vegetated and plant-shaded walls help buildings become more energy efficient and reduce the urban heat island effect, absorbs storm-water, and leads to reduced carbon emissions. It acts as a protective barrier which provides better solar protections that can reduce the effect of the external load and the cooling need (Caplow et al 2008). A number of studies have explored the thermal effect of vegetation on and around the building skin. Wong et al argued that vertical greenery systems can reduce air conditioning load by shading walls and windows from incoming solar energy resulting in a 5.5 °C reduction in the outdoor ambient temperature and shading effect was found to reduce cooling load by about 23% resulting in an 8% reduction in annual energy consumption [8]. Through simulation, 100 % greenery coverage with plants of higher shading coefficient, proved to achieve a 17.93% drop in cooling load (Wong et al 2010). Moreover, that the external surface of a vegetated wall is up to 10°C cooler than an exposed wall; therefore the U-value for the green wall is usually lower and helps to reduce cooling loads.

In addition to absorbing heat and increasing thermal performance, plants and trees can be used as barriers against urban noise pollution. Plants and the trapped layer of air can absorb, reflect or deflect sound waves. Therefore, vegetated and plant-shaded walls have
an acoustical insulation that is far better than that of bare wall (up to 30 db reduction) (Kontoleon & Eumorfopoulou 2010). The degree of sound insulation provided depends mainly on factors that influence noise reductions including depth of the growing media, type of plants, and the cavity between the plants and the wall. Plants and trees can also improve human health, capture airborne pollutions and filter harmful gases.

3 Case study

3.1 The Use of Plant-Shaded Walls

As part of an experimental work of a research project carried out by the authors (Haggag, Hassan and Elmasry 2014), two identical semi-attached housing units have been selected to investigate the thermal performance of plant-shaded walls in the hot climate of Al Ain City. As shown in figure 1, the external walls of the first house are unshaded walls (bare walls), however the building façade of the second house is shaded with non-deciduous trees (plant-shaded walls). Non-deciduous shade trees, or evergreens, do not drop their leaves during the year like deciduous trees, which lose their leaves in winter (figure 2).

The external walls of the case studies are constructed from hollow concrete blocks with thickness of 20 cm. The internal surface of the walls is covered with white stucco, however the external surface is cladded with light color stone and stucco, using wet-fixation method (without thermal insulation layer). The glass windows nearly cover 60 percent of the building façades.
Al Ain, which is the second largest city in the Emirate of Abu Dhabi and the fourth largest city in the United Arab Emirates has a desert climate with year-round sunshine. It is characterized by scarce rainfall and high levels for temperature. Summer sunshine averages 11 hours a day, falling to about 8 hours a day in winter. In summer (May to September), the weather is very hot with daytime temperatures ranging from 35°C to 50°C. During the winter (December to February), the daytime temperatures range from 25°C to 35°C, and sometimes falling to as low as 9°C at night. Rainfall is infrequent and falling mainly in winter, with an annual average rainfall of 10 cm [5]. Rainfall is very rare and falling mainly in winter with an average of 12 cm per year.

3.2 Experimental Set Up
Two identical residential building façades (Façade A and Façade B) have been tested during summer 2015: one with external bare wall and the other with plant-shaded wall. Both are facing the south-eastern direction (figure 3). To determine the temperature regulation effect of plant-shaded wall on indoor spaces, temperatures at four locations were recorded for both façades, using “DaqPRO” Omega data loggers: a) outdoor ambient air temperature (1m outside from the external wall); b) external surface temperature; c) internal surface temperature; and d) indoors air temperature (1 m inside from the internal wall).

![Figure 3: Positions of thermocouple wires for measuring wall surface and ambient temperatures](image)

Al Ain has stable weather conditions and the solar radiation intensity and ambient temperature remained fairly stable during the experiment. In order to approximate a uniform irradiation and ambient temperature transition across the day, the time steps for measurements were kept at 10 min. In order to truly represent the prevalent weather conditions i.e. higher irradianec and higher heat load conditions and avoid the intervention from occupancy of the houses the summer holiday season was selected to test unoccupied buildings. The experiments were conducted from end of June to mid-August 2015, to guarantees the highest ambient temperature and solar radiation intensity based on historical weather data to observe the impact of the plantation on heat insulation and the resultant cooling effect produced on indoor residential spaces. During this period, sun angles were studied through the “Sustainable by Design tool”. Orientations of the building façades were taken into consideration as well as the times when the sun has a perpendicular azimuth on the façades.

3.3 Results and Discussion
To understand the impact of heat transfer through the plant-shaded wall, the temperature mapping across and surrounding was conducted. The solar radiation incident on the bare wall started heating the external wall surface un-interrupted, however in the case of the plant-shaded wall, the radiation was partially blocked by the plants which produced shading on the wall surface and yielded temperature drop. To investigate the cooling effect
of the plant-shaded wall, temperatures at four locations are presented: external surface temperature, internal surface temperature, external ambient temperature and internal air temperature for the tested duration. Figure 4 maps that the peak external surface temperature on both the bare wall and plant-shaded wall for several days of measurements in July, 2014. It shows that peak external surface temperature reached around 55 ± 0.5 °C on most of the days, while the temperature on the external plant-shaded wall peaked around 49 ± 0.5 °C for most of the experimental duration. Thus, a reduction of around 6 °C can be achieved on the external plant-shaded wall surface. The reduced external surface temperature on the shaded wall naturally resulted in a reduction of the internal wall surface temperature compared to the internal wall surface temperature of bare wall as shown in Figure 5. The internal surface temperature of the bare wall peaked at 51 ± 0.5 °C, while that of the plant-shaded wall peaked at 45 ± 0.5 °C for most of the days which shows a drop of 6 °C. As shown in figures 4 and 5, the magnitude of temperature regulation at the internal wall surface is similar to the trend of temperature regulation of the external wall.

![Figure 4: External surface temperature of the bare and plant-shaded walls for several days in July](image)

![Figure 5: Internal surface temperature of the bare and shaded walls for several in July](image)

As shown in Figure 6, the indoor air temperature for plant shaded wall remained lower than that of the bare wall. However, despite the fact that the indoor ambient temperature of the plant-shaded façade has dropped by 5 °C (see figure 6), the plant-shaded wall still could not reduce the indoor air temperature to reach the comfort temperature of 26–28 °C. It means that in such a hot climate, the use of plant-shaded wall only cannot be enough and would need a mechanical cooling systems for comfortable indoors climate. The main benefit of using plant-shaded wall however comes from the reduced peak air conditioning demand.
The study observed that the temperature difference between the bare wall and plant-shaded walls is positive during day time which reduces the cooling load of the building, while; at night time the temperature difference is negative. It means that the external surface of the bare wall cools faster than the external surface of the plant-shaded wall. This shows that in a colder climate, this insulation effect of the plant-shaded wall can be exploited to keep heat absorbed during day time indoors from escaping to the outdoors and keep the space warmer for thermal comfort. In hot climates, this would tend to reverse the ambient cooling effect by plant-shaded wall at night by reducing the external wall cooling rate. As shown in figure 7, the diurnal temperature difference between the bare and shaded wall is consistently peaked on average at 10 °C.

As shown in figure 8, the plant-shaded wall internal surface remains cooler than the internal bare wall surface with an average consistent temperature difference of 6 °C, reaching up to 10 °C at peak times. At night time, this difference drops to negative, thereby reducing the cooling effect of the plant-shaded wall overall. As an average temperature drop between day and night still shows a positive outcome which means that even though, the bare wall tends to cool more than the shaded wall at night, the day time cooling of shaded wall results in a reduced overall cooling load.
The diurnal indoor air temperature differences between the bare and plant-shaded walls are shown in figure 9. The plant-shaded wall, at most of the time, maintains a lower temperature than the bare wall ranging from 8 °C during peak day-time to -4 °C during the night-time. At night-time, the indoor air temperature difference is generally negative which means that the plant-shaded wall saves energy during day-time by keeping the space from overheating, however at night-time, the effect is reversed due to the fact that at the beginning of night-time, the bare wall cools at a higher rate compared to plant-shaded wall resulting in a lower temperature at night-time.

The average temperature reduction achieved by the plant-shaded wall on the external surface, internal surface and indoor space between day- and night-times reflects the cooling energy saving. As shown in figures 7-9, the average drop of 6 °C, 5 °C and 3 °C is observed of external surface, internal surface and indoors air temperatures respectively. The drop in average temperature represents the energy saving and the drop in peak temperature represents the reduction the capacity of the HVAC system to be installed.
To determine the effect of the plant-shaded wall on cooling energy savings in the case study, a living room space was simulated in eQuest, using Al Ain weather data. The construction details and building materials of the test room were specified. The indoor control conditions were kept at 25 °C temperature and 0.5 Air Changes per Hour (ACH). The result shows the cooling load for each month with a reasonably profile of the cooling need with a peak in the months of June and July which is in agreement with the weather conditions of Al Ain city. In order to compare the results, the heat removal rate to keep the indoor air at control temperature was calculated from the measured outdoor temperature and the fixed indoor comfort temperature of 25 °C, using the following equation:

\[ Q = \rho V C_p \Delta T, \]

where \( Q \) and \( V \) are heat removal and the volume flowrate of air respectively, \( \rho \), \( C_p \) and \( \Delta T \) are the air density, specific heat capacity and temperature difference between outdoor ambient and indoor control temperature. The results show that the simulated and experimental temperature is in close agreement. The heat gain from the plant-shaded wall was processed to calculate the cooling load and compared with the cooling load of the bare wall. As shown in figure 10, the use of plant-shaded wall can reduce cooling load from 1.30 MWh/year to 1.09 MWh/year in the tested space (predicted based on average daily savings) resulting in 18.5% energy saving for cooling system.

4 Conclusion

Improving the ecological performance of building development and improving energy performance in buildings are the main concerns of urban development in the United Arab Emirates. The use vegetation on and around building façades has gained increasing popularity in many cities to improve thermal performance in buildings and reduce negative environmental impacts. Plant-shaded wall technique was successfully adopted in Al Ain, the Garden City, to increase energy efficiency and reduce cooling load in residential buildings. The study finds that plant-shaded façades can reduce the yearly cooling load saving up to 18.5 % comparing to the unshaded façades. A reduction of 6 °C can be achieved on both the external and internal surfaces of plant-shaded façade. Thus, the indoor air temperature has dropped by 5 °C for the month of July. The decreased temperature caused by the shading effect and heat resistance is due to low thermal energy gain through plants acting as heat insulators to the ambient heat gain by the wall. Plant-shading technique contributes to LEED credits since it covers issues like energy saving, air quality, and sound reduction. Despite its advantages, plant-shading strategy requires economic justification to get a clear picture of the real economic incentives.
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References


A SIMULATION VERIFICATION OF SUSTAINABLE GEOTHERMALLY-HEATED HOUSE IN COOL CLIMATES

Koon Beng Ooi¹ & Masa Noguchi ²

¹ Adjunct Research Fellow, Faculty of Science Engineering and Technology, Swinburne University of Technology, Australia, kooi@swin.edu.au
² The University of Melbourne. Faculty of Architecture, Building and Planning. Melbourne School of Design, Buildings 133, VIC 3010, Australia, masa.noguchi@unimelb.edu.au

Abstract: Heating is required for residential buildings in climates like or cooler than that of Melbourne, Australia's cool temperate. Here, water from 100-meter-deep U-tubes (ground heat exchangers, GHE's) has been measured at a stable 22-24°C, and many detached houses have land for a few GHE's. The hypothesis is that, by circulating this warm water to low-temperature radiators (LTRs) on the inside faces, houses become cave-like with thermally comfortable indoors. EnergyPlus is used to model a GHE and LTRs for a 60m²-Melbourne house, to be used for experimental validation of simulated results. Simulations show that with three water pumps that use a total of 44 W, running from 7 am to midnight, during winter, a 23°C-bottom temperature GHE and LTRs on two opposite walls heat the 30m²-Living Area and 30m²-Bedroom to the heating thermostats in the Nationwide House Energy Rating Scheme (NatHERS). Except for 2 days in summer, the indoors are cooled below 26.5°C, (the temperature above which NatHERS uses energy to cool houses in Melbourne climatic zone). During summer, fans that provide thermal comfort for up-to-31°C environment can replace the LTRs to cool the indoors, and solar-heated water from 30 evacuated tubes, can return 1.2 MWh heat to the GHE's. For this 60m²-house, simulation shows that GHE-heat extracted in winter is 0.5 MWh; therefore, geothermal heat is sustainable for, by proportion, 144 m² (family size) houses. Since power for the water pumps plus, the cooling fans in summer or, exhaust fans to draw ventilation air through a GHE-heated preheater in winter, can come from onsite solar photovoltaics and batteries, houses are passive. Knowledge of the local geology and temperatures below 15 meters would enable sustainable GHEs and economical LTRs to be incorporated into the design, by simulation, of affordable passive, comfortable houses in climates like or cooler than Melbourne's.

Keywords: Sustainable geothermally-heated houses, cool-climates, hydronic-radiators
1 Introduction

Traditionally, a vertical ground heat exchanger (GHE) serves as a heat source/sink for the geothermal heat pump, and water-to-water heat pumps deliver about 50°C water to metallic radiators. The hypothesis is that, at a certain depth below 15 meters, the temperature is stable and around those for thermal comfort. Therefore, water heated by such GHE/s can be circulated directly to low-temperature radiators (LTRs) on the inside faces to make houses cave-like and thermally comfortable. This hypothesis is proposed with the following five information and assumptions.

1. The temperature of water from 100 meter-deep GHE in Victoria, Australia has been measured at 22-24°C. This is 2-4°C hotter than the highest heating thermostat of 20°C in the National House Energy Rating Scheme (NatHERS 2016), and placed in walls, would make indoors thermally comfortable in winter.

2. Most variations of the indoor heat are from slow heat transfers through the building envelope. Variations of indoor heat due to number and activities of residents are quicker but are small fractions of the total heat load. With good view factor between residents and walls, radiative heat transfers could provide thermal comfort.

3. Cooling can cause condensation. Therefore, hydronic radiators are used only on the walls and not at the ceiling or floor. Drains can be made on the floor below these LTR walls and used if air movement cannot dry the condensates.

4. In cool/cold climates, GHE heat can be sustained by circulating water from solar collectors to GHE in summer. Cooling by LTRs is replaceable with fans, which can make up-to-31°C operative temperature-environments thermally comfortable. (Fountain, M. & Arens, E. A., 1993)

5. In winter, ventilation air may be preheated by heat exchanger-exhaust fans. The 'fish-tank'-size water pumps, fans in summer or fresh air preheat system in winter can be powered by onsite solar photovoltaic and deep cycle batteries.

Many parts (green and blue in Figure 1) of the world, e.g., America (especially North America), Canada, Europe, China and New Zealand have annual average air temperatures cooler than the 15°C of Melbourne where "star-rated homes require heating". (Australian Government Department of Industry 2016)
2 Literature Review

2.1 Inter-seasonal Storage (Summer’s Solar Heat for Winter Use): Problematic.
Arnould, M. (1985), Oliveti G.& Arcuri N (1995), Oliveti G. et. al. (1998) and Kroll, J.A. & Ziegler, M. (2011) studied inter-seasonal storage of solar-heated water. Kroll J.A. & Ziegler M. (2011) concluded that for small residential buildings, the ground could be used for inter-seasonal storage. “The loss of heat is acceptable if the ground storage is cuboidal shape and must be heat-insulated and damp-proof” implies that after 3 decades of research, storing summer heat for winter is still problematic...

Ooi, K. et. al. (2015) showed by simulations, that during the hot half of the year, 30 evacuated tubes could collect 1.2 MWH of heat. By the end of summer the temperature of solar-heated water in the 2-m³ indoor tank of a 30m²-Melbourne house is 50°C and, by end winter, is 20°C. Also, Michael O’Connell had, on 2/5/2016, emailed to inform that hydronic heating sellers had used 5-m³ water storage, and many of these systems were struggling to provide 2 hours of effective heat. Therefore, the size of the indoor tank could be too large for a family-sized house.

2.2 Below 15 meters, the temperature increases with depth.
“... At depths below about 15 meters, ground temperatures are affected by the small amount of heat conducted upwards from the sub-surface. In the UK, this creates an increase of temperature with depth that has an average value of 2.6°C per 100 meter. This geothermal gradient will vary depending upon the nature of the rocks and their thermal properties” (British Geological Survey 2011). IPCC 2008 estimates this gradient at 25-30°C/km. Therefore, for places with Melbourne’s 15°C average annual air temperature the desired 2-4°C above the 20°C heating thermostats would be at around 300m depths.
At Swinburne University of Technology's Wantirna (latitude -37:52:12, longitude -145:14:13) campus, South Eastern Melbourne Australia. 22-24°C water is from 100-meter deep GHE (Vince Persi email dated 8/4/2016). At about 10 km away, where experiments are being carried out, water from a 50-meter-deep GHE has been measured at 15-17°C (Ooi K. et al 2015). The upper layer is sand and transitions to hard siltstone between 8 and 20 meters (Donald Payne email dated 27/8/2014).

2.3 Theory behind EnergyPlus's vertical ground heat exchanger (GHE) model
The long and short time response factors (g-functions) of borehole temperature responses was respectively studied by Eskilson, P. (1987) and Yavusturk, C. and Spitler, J.D. (1999). g-functions are infinite series of numbers, which relate the current value of a variable to past values of other variables at discrete time intervals.

The US Department of Energy (2016) developed the variable, short time step model that accommodates sub-hourly responses, variable time steps and explicit equations to calculate the outlet fluid temperature of the ground loop heat exchanger (US Department of Energy, EnergyPlus Engineering Reference, 2016:1203). US Department of Energy EnergyPlus Reference (2016: 1204-1209) describes the load aggregation scheme developed for energy simulation software with variable short time steps down to one minute. The results presented in this paper are based on simulations that use the 35 pairs of non-dimensionalized times and g-functions given in EnergyPlus example files.

2.4 Validation of EnergyPlus's LowTemperatureRadiant model of the LTR
The LTR is modelled by the EnergyPlus LowTemperatureRadiant:VariableFlow object. Chantrasrisalai, C. et.al (2003) validated EnergyPlus Low-Temperature Radiant models, and concluded that “good agreements between predicted and experimental results can be achieved in the EnergyPlus low-temperature radiant simulation by adjusting appropriate input parameters that can have an impact on the systems”.

The proposed 60m² experimental building is an extended metallic garage and the thicknesses of the polystyrene insulation material can be adjusted to vary the building surfaces' R-values during the experiments to validate simulated results. The LTRs on the two opposite (North-West and South-East) walls are constructed with affordable 13mm diameter polyethylene tubing, spaced at 100 mm apart.

2.5 Maximizing the performances of a wall with Water inside
Trancossi, M. et. al (2016) presented optimization guidelines of a wall with water inside with the objective of maximizing the performances of the wall for reaching optimal internal wellness conditions. “If circulating water is thermally stabilized by exchanging in the ground such as it happens in geothermal plants, a thermal shield could be realized keeping walls in comfort conditions and minimizing energy needs for further temperature regulations”

2.6 Victoria's share of national space heating energy, Cost of “Passive Houses”
The Department of Energy, Water and Housing of Australia (DEWHA, 2008) reports that in 2007, the state of Victoria accounts for a 59% share of the national space heating energy consumption. The term passive house (Passivhaus in German) refers to a rigorous, voluntary standard for space heating energy efficiency in a building, reducing its ecological footprint. It results in ultra-low energy buildings that require little energy for space heating or cooling. The average passive houses are ... more expensive upfront than conventional buildings by - 5% to 8% in Germany, 8% to 10% in UK and 5% to 10% in USA (Wikipedia: Passive House 2016).
3 Method

3.1 A 60m² house that enables experiments to validate the simulated results

Figure 2 shows a plan with the orientation of the proposed 60m² experimental building in Mulgrave, Victoria, Australia. The 30m² flat-roofed 2.4mH ceiling height bedroom is proposed to be next to the existing 30m² double-sloped-roof, 2 to 2.4mH metallic garage, zoned as the Living Area / Kitchen.

The concrete floor of the existing garage is thermally-bridged to the concrete driveway on the South-West side. The concrete floors would be covered with damp-proof vapour seal plastic, polystyrene and wood. Table 1 tabulates the materials used at each surface, thickness, conductivity and calculated R values. During experiments to validate the simulated results, the R-values of the surfaces can be adjusted by varying the thickness, of especially the polystyrenes.

![Figure 2: 60m² Experimental Building- Plan, Orientation](image)

Table 1: Materials for the surfaces for the 60m² experimental house

<table>
<thead>
<tr>
<th>Surface</th>
<th>Material</th>
<th>Thickness</th>
<th>Conductivity</th>
<th>Material R-value</th>
<th>Surface R-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls (NE &amp; SW)</td>
<td>F08 Metal</td>
<td>.08</td>
<td>45.28</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R3.5 Batt Insulation</td>
<td>110</td>
<td>.04</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G02 12mm plywood</td>
<td>12</td>
<td>.12</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>F08 Metal</td>
<td>.08</td>
<td>45.28</td>
<td>0</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>R5 Batt Insulation</td>
<td>200</td>
<td>.04</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G02 12mm plywood</td>
<td>12</td>
<td>.12</td>
<td>.1</td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>Concrete</td>
<td>51</td>
<td>1.95</td>
<td>.0262</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vapour seal plastic film</td>
<td>.</td>
<td>.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polystyrene</td>
<td>70</td>
<td>.029</td>
<td>2.4138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G06 50mm wood</td>
<td>50.8</td>
<td>.15</td>
<td>.3387</td>
<td></td>
</tr>
<tr>
<td>LTR Walls (NW &amp; SE)</td>
<td>0.1m tube spacing</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R2.5 Batt Insulation</td>
<td>110</td>
<td>0.04</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G04 13mm wood</td>
<td>12.7</td>
<td>0.15</td>
<td>.0847</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expanded Polystyrene</td>
<td>25</td>
<td>0.02</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Plasterboard</td>
<td>13</td>
<td>.</td>
<td>.056</td>
<td>4.1407</td>
</tr>
</tbody>
</table>
3.2 Temperatures beneath (on the outside face of) the Floor

The temperatures on the outside face of the building surfaces are needed for EnergyPlus 2-D computations of the heat flows through them. For the floor of conditioned indoors, EnergyPlus 3-D ‘Slab’ preprocessor can simulate for the temperatures beneath the floor using the monthly average indoor temperatures. Since the LTRs are expected to make indoors thermally comfortable during the cold months, the weighted average of NatHERS heating thermostats of 18.35°C are used for June to September. Slab simulations based on a soil thermal diffusivity of 2.3225760E-03 m²/day show that the temperatures beneath the floor converged after 8 years and Table 2 shows the monthly averaged temperatures beneath the floor. The minimum, from June to August is about 16.55°C, or about 2°C lower than the conditioned indoor temperatures', which, according the EnergyPlus documentation, can be used as approximate values.

| Table 11: Temperature [°C] beneath floor, indoors heated to thermal comfort in winter |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|       Jan   |       Feb   |       Mar   |       Apr   |       May   |       Jun   |       Jul   |       Aug   |       Sep   |       Oct   |       Nov   |       Dec   |
| Indoor    | 26.18    | 26.6    | 13.13   | 20.5     | 18.35    | 18.35    | 18.35    | 18.35    | 18.35    | 18.35    | 20.87    | 22.66    | 24.79    |

3.3 Modelling the Ground Heat Exchanger: Vertical (GHE) plant and the LTRs

There is one 50m-deep GHE and another 2x25m-deep GHE next to the experimental house. The temperature of the water from the 50m-deep GHE is 15-17°C. The GHE plant is modelled by EnergyPlus's GroundHeatExchanger:Vertical object. Table 3 shows the data for each of the fields of this object. The 1.58 W/m-K Ground Thermal Conductivity is for siltstone, because the boring for these existing GHEs reveal sand that transitions to hard siltstone below between 8-20 meters. The thermal conductivity of the grout is 1.98 W/m-K (Donald Payne email dated 27 August 2014).

| Table 12: Data for EnergyPlus GroundHeatExchanger:Vertical (GHE) object |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Number of Boreholes | 1 |
| Borehole Length (m) | 100 |
| Borehole Radius (m) | 0.05 |
| Ground Thermal Conductivity (W/m-K) | 1.58 |
| Ground thermal heat capacity (J/m³-K) | 2218500 |
| Ground Temperature (°C) | 22,22.5, 23 |
| Grout Thermal Conductivity (W/m-K) | 1.98 |
| Pipe Thermal conductivity (W/m-K) | 0.39 |
| Pipe Outer Diameter (m) | 26.67 |
| U-tube Distance (mm) | 25.39 |
| Pipe Thickness (mm) | 2.41 |
| Maximum Length of Simulation (Years) | 2 |
| G-function Reference Ratio (dimensionless) | 0.0005 |
| Number of Data Pairs of the G-function | 35 |

Figure 3 shows the common pipe that is used to store water for both the GHE plant (Primary) loop and the LTRs (Secondary) loops. The GHE plant cannot be used for both heating and cooling in one simulation. Therefore it is used as a heating plant for the March 22-Nov21 cold period and as a cooling plant for the other 4-month hot period.
Preliminary simulations confirm that the temperature at the bottom of the borehole dominates indoor temperatures. Other variables e.g., thermal conductivity, thermal heat capacity etc. are less significant. When the GHE is used as a heating plant, simulations are run for three bottom Ground Temperatures of 22.0°C, 22.5°C and 23.0°C.

Also, the night heating thermostat for the Bedroom, set-backed to 15°C from the daytime thermostat of 18°C, is attainable with a 7am-to-midnight pump operation. This better matches the demand for electricity to availability of solar powered electricity and could prolong the life of the deep cycle batteries. No night thermostat is specified for the Living Area. Thus, simulations are run with the pumps available only from 7am to midnight.

4 SIMULATION RESULTS

Figure 4 shows the three simulated operative temperatures of the Bedroom and Living Area, during a coldest week for GHE bottom temperatures of 22°C, 22.5°C and 23°C. The vertical grids divide each day into three 8-hour periods, starting from 00:00 hours. Only when the GHE bottom temperature is 23°C, are the indoors practically above the NatHERS heating thermostats of 20°C from 8 am to midnight for the Living Area and, for the Bedroom, 18°C from 8 to 9 am and 4 pm to midnight, and 15°C from 1 to 7 am.
Figure 5 shows that because the night thermostats are set back to 15°C, there are peak demands for heat at 7-8 am. The Average Borehole temperature dropped, by about 0.5°C. Therefore, when the GHE is changed to a cooling plant in the summer months, 22.5°C is used as the bottom temperature for the GHE.

![Figure 5: Ground Temperatures and Rate of Heat Extraction during a coldest week](image)

Figure 6 shows that for 1 or 2 days in the hottest week of Jan 3-9, the outdoor temperature is above 32°C, and daytime indoor temperatures are above 26.5°C. This is the temperature (heating thermostat of 24°C for Melbourne climatic zone) plus 2.5°C, at which NatHERS start to calculate cooling energy in its star rating of houses.

![Figure 6: Living Area and Bedroom Temperatures with 22.5°C deep ground temperature](image)

Table 4 shows that a total of only 44W is required by the water pumps. This is because it is the power to only circulate water. The pumps do not need to elevate water as the water
level in the vertical common pipe for the GHE and LTRs loops is just below the ceiling and the LTRs are immersed in water all the time. Such low power is validated during preliminary experiments when a 25W fish tank pump circulated water from the U-tube to a 75-meter-long tubing LTR. The Loop Volume for the GHE indicates that this 2-meter-high common pipe has a diameter of 0.25 meter.

<table>
<thead>
<tr>
<th>Water Loop</th>
<th>LTR (Living Area)</th>
<th>LTR (Bedroom)</th>
<th>GHE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating</td>
<td>Heating</td>
<td>Heating</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>Cooling</td>
<td>Cooling</td>
</tr>
<tr>
<td>Pump Power (W)</td>
<td>1.97</td>
<td>1.97</td>
<td>39.3</td>
</tr>
<tr>
<td>Water Flow Rate (L/s)</td>
<td>0.08</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>13mm tubing length (m)</td>
<td>181</td>
<td>240</td>
<td>210</td>
</tr>
<tr>
<td>Zone Design Load (W)</td>
<td>672</td>
<td>201</td>
<td>595</td>
</tr>
<tr>
<td>Air Flow Rate (m³/s)</td>
<td>0.05</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The heat extracted during the 8 cold months is about 0.5 MWH and that returned during the 4 hot months is about 0.2 MWH. This is because Melbourne is in the cool temperate zone and the average annual air temperature is 15°C. The Zone Design load is based on an outdoor temperature of 31.9°C, which will be exceeded only for 1% of the time in a year. The total design load of about 1.2 KW is reasonable for this insulated house.

5 Discussions

Can heat from GHE be sustained? Simulations show that 30 evacuated tubes can, in summer, collect and return 1.2 MWH or heat to the GHE. This is 2.4 times the 0.5 MWH that is extracted from the GHE in winter to heat a 60m²-house. Therefore, 30 evacuated tubes can replenish the heat extracted for, by proportion, 144 m² (family size) houses. Thus, for sustainable GHE heat, use fans instead of using LTRs for cooling in summer.

Is the house passive? Is renewable energy used for thermal comfort? For this 60m²-house, the pump for the GHE needs 39.3W and to circulate water through the 400m long 13mm diameter tubing of the LTRs needs 4W (Table 4). A 0.5 KW solar photovoltaic and batteries can thus power the water pumps and, in summer, the cooling fans, and in winter, a heating system for ventilation air, for family-sized houses.

Is this LTR conditioned house affordable? The LTRs handle warm water at about 25°C, so low cost polyethylene tubing can be used instead of expensive metallic radiators. Geothermal heat pumps are likely to be costlier than 'fish tank' pumps that circulate waters, fans for cooling in summer and heating system for ventilation air in winter. Furthermore, houses conditioned by LTRs do not need the ducts that are commonly placed in the attic to distribute conditioned air; so, roofs can be flat and more affordable than sloping roofs.

6 Conclusions

EnergyPlus simulations verify that about 100-meter-deep vertical ground heat exchanger and hydronic wall radiators could sustainably heat a 60m² Melbourne house to thermal comfort in winter. Without the traditional heat pump, such direct geothermally-heated family-sized houses are likely to be more affordable. Readily available photovoltaic and batteries can power the water pumps and fans to condition the indoors to thermal comfort throughout the year. Experimental validation can be carried out and knowledge of the local geology and temperatures below 15 meters could enable EnergyPlus to design
sustainable affordable passive family-sized houses in the many climates that are like or cooler than Melbourne’s cool temperate.

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References


RESPONSIVE RETROFIT MEASURES FOR TRADITIONAL LISTED DWELLINGS: AN INVESTIGATION INTO A MIXED METHODS APPROACH

Michela Menconi\(^1\), Noel Painting\(^2\) & Poorang Piroozfar\(^3\)

\(^1,2,3\) School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, East Sussex, UK

M.menconi3@brighton.ac.uk, N.J.Painting@brighton.ac.uk, A.E.Piroozfar@brighton.ac.uk

Abstract: The body of scientific research corroborates that reducing energy consumption alongside other environmental impacts can help reduce climate change effects. Existing buildings are major contributors to energy consumption and carbon/GHG emissions. Even more so is the housing stock, and more specifically, the dwellings of some cultural value or heritage merit. In the case of historic dwellings, because of constraints imposed by their heritage value, improvements are not as easy as for the rest of the existing building stock. The UK must address retrofit measures in this sector as it inherits one of the oldest, most culturally-rich yet most poorly-performing housing stocks in Europe. This paper sets out to elaborate on the methodology developed for a research project aimed at devising a framework for interventions in traditional listed dwellings to improve the environmental impact at reasonable cost, in order to shape a more future-proof heritage by providing decision support structures for stakeholders groups. The paper concentrates on the proposed mixed methodology, which is centred on a selection of C.19th case study dwellings in Brighton, South East of England. Following a critical literature review, secondary data collection and analysis, interviews/questionnaires, measured surveys, data logging, thermal imaging and energy simulations are proposed in order to investigate the current energy performance and the possible improvements to suggest responsive and cost-effective energy retrofits of the selected dwellings.

Keywords: Energy retrofit, Sustainable refurbishment, Cultural Heritage, Housing, Listed buildings
1 Introduction
This paper describes the methodology and methods developed for an ongoing study aimed at devising a framework for intervention in traditional listed dwellings (TLDs) to improve their environmental impact. The research seeks a solution based on an overall sustainable approach; one that takes into account socio-cultural aspects, environmental aspects and economic aspects. For the purpose of this study, a pragmatic philosophical position has been adopted that will opt for the use of more than one research strategy in order to gather data in a variety of ways to investigate the problem in-depth and guarantee reliability of the results generated triangulating data sources. Such approach is what this paper aims to address.

The novelty of this study lies in the comprehensive account and unique combination of a mixed method approach on multiple case studies for the analysis of the current performance and the possible energy improvements of TLDs. The combination of a carefully selected set of appropriate methods should allow for gathering a whole set of qualitative and quantitative data to be collated, analysed and inputted in an environmental simulation software in order to achieve models as close to reality as possible. Such comprehensive, multifaceted and multi-criteria approach to environmentally concerned interventions can particularly be recommended for heritage buildings to mediate between environmental and conservation issues with a sensible account of cost and financial aspects. Academics, practitioners, legislative bodies and policy makers in local and central governments have repeatedly called for the need for such methodology to justify a systematic decision making for performance improvement in this sector.

2 Rationale for research
The Intergovernmental Panel on Climate Change (IPCC 2014) stated that anthropogenic activities are the main cause of global warming today, being responsible for increasing concentrations of greenhouse gases (GHG). To face this threat, the UK has committed to lowering emissions by at least 80% by 2050 as compared to 1990 levels (Climate Change Act 2008).

The built environment is responsible for about half of these emissions in UK (UK-GBC 2014) and the housing sector produces about one quarter of the total GHG emissions (HM Government 2009) mainly due to space heating (HM Government 2012). Furthermore, most of the 25 million homes existing today in the UK are expected to still be in use by 2050 (Wright 2008). The built environment therefore, and in particular the housing stock, can surely play a major role in mitigating climate change. The UK, however, is facing a major challenge to address retrofit measures in this sector as it inherits one of the oldest, most culturally rich yet most poorly performing housing stocks in Europe. Approximately one quarter of the total number of dwellings in UK, are so-called traditional buildings (STBA 2012a). This definition applies to dwellings built before 1919 - which is widely known as the date for the introduction of DPC and cavity wall construction in the UK (English Heritage 2008) - with solid permeable walls (Historic England 2011). Most of these buildings are generally poorly performing (Boardman 2007).

The problem becomes even more complex considering that about one quarter of the traditional housing stock in the UK is listed or within conservation areas (Bottrill 2005). These are buildings of special architectural merit and/or historic interest therefore protected to guarantee their conservation. However, the listing makes their energy upgrade particularly challenging as any retrofit measure has to be weighed against the damage it may pose to their heritage value. A report by the Sustainable Traditional
Buildings Alliance (STBA 2012a) has also evidenced how it is still uncertain what can be achieved with typical retrofit measures without damaging the heritage. This is mainly due, according to the report, to a lack of proper understanding of how traditional buildings operate as well as of the effects of an energy efficient refurbishment on them.

To be able to properly evaluate how they actually operate, more research is needed firstly to thoroughly investigate their fabric and understand how it behaves, then to translate this knowledge into models and simulation software to assess their current energy performance. Finally, responsible solutions for them will be devised carefully balancing energy upgrade measures and conservation issues. This needs to be carried out weighting the trade-offs between interventions, improvements as a result of such interventions and cost implications while considering the impacts on the historic and architectural values perceived to be inherent characteristic of this section of the heritage.

3 Aim and Objectives

This paper attempts to present the methodology and methods developed for a research aimed to provide a framework to intervene, within the set boundaries of the relevant legislation and regulation, in TLDs to improve their environmental impact within a reasonable cost bracket in order to shape a more future-proof heritage.

To successfully achieve the aim of this research, the following objectives need to be fulfilled successively during the different stages designed for this study:

1) To identify the actual energy use, CO₂ emissions and other related environmental impact categories of TLDs.

2) To investigate the range and extent of possible retrofit interventions within the context of legislation, regulation and guidance applicable to listed buildings.

3) To investigate the impact of the selected possible interventions on TLDs with reference to their historic fabric, CO₂ emissions, energy consumption and other environmental impact categories.

4) To define a methodology to propose appropriate combinations of retrofit solutions to apply to TLDs with reference to performance, legislation, regulations, heritage values and cost implications of such solutions, so that an overall sustainable approach to such measures can be taken.

4 Critical literature review

A critical review of literature has been conducted in order to aid in the definition of the research design, methodology and methods to be adopted for this study. Examining the documents related to energy performance of existing buildings in their unimproved condition and after retrofit, it is immediately evident that the majority of the research is concerned with retrofitted buildings, while very limited work has been done to investigate their performance in the original condition (STBA 2012a). This is however fundamental knowledge to take into account when setting out effective interventions and is the starting point for any calculation of the benefits of the measures to be adopted (Moran 2013; Panayiotou 2014).

The initial critical review has been done of the state of the art literature on the energy performance of existing dwellings in their unimproved condition. Looking at residential buildings, the research conducted by Panayiotou (2014) attempted to define a model representative of the whole range of dwellings in Cyprus. The study adopted
questionnaires to gather data about a statistical sample of 500 properties; from the analysis of the data collected, a model house was designed that summarised the characteristics of the majority of the dwellings in Cyprus. On such a model, different energy conservation measures were tested using software simulation. The study, however, concluded asserting that, in order to properly evaluate the thermal insulation combinations suggested and to validate the theoretical results obtained on the modelled typical house, it would be useful to check the simulation results with outdoor experiments under real conditions. A similar approach for the definition of a baseline of performance was adopted by Akande et al. (2015) investigating six grade I listed churches as case studies using a questionnaire survey. However, no simulation has been done of the buildings performance before and after retrofit interventions and the study could only conclude suggesting the adoption, coupled with behavioural changes, of careful measures that respect the heritage value.

The literature review conducted indicates that only a few studies have involved listed or historic dwellings in their entirety. The research carried out in Scotland by Ingram (2013), made use of steady state (SAP and RdSAP) and dynamic simulation (IES-Ve) tools in five case study traditional dwellings to assess their energy performance and compare the quality of the results given by the different methods. The simulated energy demand was compared against measured data only in one case, hence the study concluded suggesting the importance of extending such methodology to a much wider range and number of cases. The approach taken by Moran (2013) in Bath with historical dwellings proved to be also workable elsewhere. His methods involved the use of a questionnaire survey about domestic energy consumption on a selected representative sample of the population of historic dwellings to define a baseline for interventions. The results were then matched with national statistics about energy use. Finally, three case studies were used to model their energy consumption using three steady state assessment systems and one dynamic modelling tool and validating the predicted energy use results against actual energy use data. Such an in depth analysis, however, has been carried out in this study with the main purpose of confronting the results obtained from a dynamic software with those given by steady assessment tools and determine the loss of detail as a result of adopting steady state models.

Conspicuous is the body of research produced by Historic Scotland and Historic England on the analysis of traditional buildings performance; however it mainly looks in detail at one or more elements of the external envelope like windows (Baker 2008; Wood at al. 2009) or walls (Baker & Rhee-Duverne 2012), or specifically at their U values (Baker 2008, 2011) or investigates the potentialities of energy simulation software for accuracy in the evaluation of the building energy performance (Barnham et al. 2008; Heat et al. 2010; Ingram & Jenkins 2013; Jenkins 2008). A more holistic approach has been adopted by Ascione et al. (2011) investigating in-depth a single case study in order to define possible improving interventions. The object of the research was a public historic building in South Italy. The study proposed a methodology for the performance analysis, coupling several experimental studies and simulations; the careful combination of them generated a model as close as possible to the real building. It was also validated comparing the results of the energy simulation with the meter reading of gas and electricity. Subsequently, the dynamic energy simulations were used to test the effectiveness, singularly and coupled, of several solutions for the building energy upgrade. This approach guarantees an in-depth understanding of the building’s materials and techniques and the generation of a realistic model but does not prove to be easily applicable on the whole body of historic dwellings due to the invasiveness of the experimental studies involved.
From the literature review conducted it seems that a holistic approach (Boardman 2007) is widely agreed as the most suitable one for traditional buildings, to improve the energy performance with low impact interventions that respect the character of the building in order to allow our heritage to withstand future challenges; such approach has rarely been adopted with this purpose and only limited to few case studies while the need for a major number of cases has been repeatedly been called for.

A literature review has also been used to investigate the potentialities of simulation methods for the analysis of the building energy performance. Such a method is a validated strategy used to assist in the design process of energy efficient buildings (Garber 2009; Nguyen at al. 2014; Wang at al. 2005; Fesanghary et al. 2012) as well as in the choice of suitable retrofit interventions on the existing stock (Ascione at al. 2011; Ascione at al. 2015; Kolaitis et al. 2013; Pernigotto et al. 2012; Stazi et al. 2013). Nevertheless, when it comes to traditional buildings, there are still some important concerns with regards to the proper application of models and performance simulation software to investigate the energy consumption of this part of the stock (STBA 2012a, 2012b). Previous research on the subject of performance and energy efficiency of traditional buildings has frequently highlighted a gap between current monitored research evidence and most modelling of traditional building performance (Barnham et al. 2008; Heat et al. 2010; Ingram & Jenkins 2013; Jenkins 2008; Moran 2013, STBA 2012). Comparing Leeds Metropolitan’s study (Wingfield et al. 2011) and Good Home Alliance one (Thompson & Bootland 2011; Taylor & Morgan 2011) on the performance gap for new build, with works by Rye (2010), Baker (2011) and Hubbard (2011) on traditional buildings, it emerges how the performance gap between the model of a traditional building and as-built reality may be considerable. However, while new buildings' performance is frequently overestimated by the simulation, research has demonstrated how traditional buildings often perform much better than expected because of processes and synergies that are not well seized by models. Although it is not the main focus of this research, this finding was considered to be relevant to take into account in this study because, if the secondary strategy of data collection was not workable and this research was only to rely on simulation, it will be assured that the results obtained by the energy modelling per-se will be sitting on the safe side providing a worst-case baseline scenario for the interventions to apply.

5 Methodology and Methods

For the specific nature of this research, its aim, objectives, data types and analysis required, a pragmatic philosophical approach has to be taken, hence a mixed method strategy (Creswell 2014) which starts with critical literature review and secondary data analysis to build up the underlying frame for collection and analysis of primary data through a multiplication of different methods. The literature review conducted on similar studies and summarised above has evinced how an holistic approach as such is unprecedented if not for single case studies and proves to be the most suitable to take into account all the complex synergies that characterise historic buildings.

5.1 The setting

Before moving to the data collection and analysis phase of this study, it is important to set the research within the location chosen and explain the rational for the selection of this context. The City of Brighton and Hove has been chosen as the geographical setting due to the full combination of different influential factors that it provides, which make of it an extreme case within the English housing context.

Brighton is centrally located within the South East of England, which has the highest predicted temperature rise for the future time period of 2080s (Jenkins et al. 2009). Most
of the historic buildings in the city belong to the early 19th century. At that time Brighton turned into a spa town and seaside resort and flourished with notable examples of regency architecture (Antram & Morrice 2008). The Council recognises these buildings as possessing a great heritage value, hence the significance of the special care owed to the preservation of their character (Brighton and Hove City Council 2009). This places constraints on retrofit measures for such buildings when the interventions may affect their fabric and aesthetics.

The city of Brighton and Hove has a remarkably large number of pre 1919 dwellings (The definition of dwelling is given by the Government’s Guidance in line with the 2011 Census definition - DCLG 2012). Of the total number of dwellings – both listed and not listed - (104.100), almost 40% were built before 1919, (Brighton and East Sussex 2008). This proportion far outweighs the considerable percentage of traditional dwellings in Britain, where approximately 25% of dwellings are traditional ones (BPIE 2011).

A substantial number of the traditional dwellings in the town are listed; 1218 in total are the listed entries. The Council is however unaware of the existence of any kind of statistic breakdown for the data concerning listed entries. From a first analysis of the list, it is evinced that more than 95% of the entries date before 1919 and approximately 750 are residential; generally though, one single residential entry refers to a cluster of individual buildings, frequently a listed terrace of houses. Therefore, the number of entries that are houses is estimated to be more than 3000. Furthermore, many of the listed residential units are magnificent regency terraced houses that have been split into four or five individual dwellings, one at each floor level. Hence, the number of listed traditional dwellings is surely higher than the total estimated number of listed residential buildings. By simply considering some of the main 19th century terraces and supposing that each house is divided into flats at each level, the total number of listed dwellings is estimated to be more than 5000. Further and deeper investigation is necessary to extract precise numbers. However, from this initial study, it can be concluded that certainly more than 12% of the traditional dwellings in town are listed.

Most of these residential estates perform poorly (Brighton and East Sussex 2008) because they were built at a time when very low energy standards were applied and because of a lack of investment in this sector. This evidence could be a consequence of the general trend in Brighton that shows a tendency to split houses into flats and rent them out leading to a high rate of deterioration. The House Condition Report (Brighton and East Sussex 2008) shows how the building type profile in Brighton & Hove differs from the national pattern with a much higher level of converted flats; over seven times found nationally. The council website (Brighton and Hove City Council 2016) states that the amount of private rented properties in Brighton & Hove is 21%, twice as much as the national average and the sixth largest private rented sector in the country.

The typical construction material in Brighton during the 19th century was “bungaroush”, a compound with uncertain thermal performance, which will possibly contribute to describe a worst-case scenario to provide findings that will be sitting on the safe side.

The combination of these factors identifies Brighton as a worst-case scenario to analyse; such setting for this research should give results that will likely prove to be easy to tailor or amend in order to propose validated solutions for similar listed properties elsewhere in the South East of England.
5.2 Case study research

5.2.1 Rational

The primary data collection and analysis phase of this research uses case studies as main approach where a multitude of different methods can be utilised to provide and support multiple units of analysis. This is because “the researcher can study information systems in a natural setting, learn about the state of the art, and generate theories from practice” (Benbasat et al. 1987: 370). Multiple-case design allows for cross-case analysis and the extension of theories. Furthermore, the use of multiple units of analysis consents triangulation and guarantees better reliability of the research conclusions (Benbasat et al. 1987). Hence, the approach of this research, where a multitude of cases have been involved and analysed with multiple methods to generate reliable, comprehensive answers to the research questions and allow comparison between the findings. Concerning the practicability of any generalization out of case studies, Tsang (2014) affirmed that cases are not to be considered as sampling units and should be treated instead as experiments. They can therefore be generalized to theoretical propositions (Yin 2013). It is of paramount importance to note that the knowledge claims, which can be made with a case study approach, are not of the same nature and application of those made using pure quantitative methods. While samples research calculates frequencies in order to provide a statistical generalization, the purpose of case study research is to expand and generalize theories. The outcome of case study approach can be what Yin calls “analytical generalization” (Yin 2014).

5.2.2 Target population and representative case studies

In order to select representative case studies for the purpose of this research, it has first been necessary to define the target population, for which the study aims to generalise its findings. This is made of all TLDs in the South East of England. At present no statistic is available to define the actual number of this population with a good degree of certainty. The only data available today refers to the whole listed entries in England: that is 376,099 according to Historic England (2015), which have been clustered based on their period in Figure 1.

![Figure 1: Historic England, 2016. Graph detailing the age range of listed buildings in the UK (2016) [online] Available from: https://www.historicengland.org.uk/listing/what-is-designation/listed-buildings/, [Accessed: February 2016].](image)

The graph illustrates that a total of 63% of the overall listing belongs to the 18th and 19th century. Looking specifically at dwellings though, a quick scan of the period of listed residential entries in Brighton, shows that the great majority of them belong to the 19th century, most of which being big regency terraces of houses (also divided into flats) listed as just one single entry. This is specific to the regency Brighton but can also be considered valid, with some decades of difference sometimes, for the whole south east of England, where the big boom of houses happened with the development of the terraced house
typology before, during and after the industrial revolution (Muthesius 1982). Therefore it is realistic to assume that the majority of pre 1919 listed dwellings in the South East of England belong to the 19th century; hence this could be, with a better approximation, the target population.

This research is using approximately 10 - 15 case studies reflecting the local 19th century listed housing stock. This sample size will be enough to allow comparative studies on the chosen dwellings (Gay & Airasian 2000). In order to decide how to chose representative cases out of this population, the proportion of grade I, II* and II dwellings has been taken into account. The list of Brighton entries reflects the trend found in England, with more than 90% of the whole population listed as grade II, the remaining as grade II* and grade I. Therefore, it has been first considered whether to use a stratified sampling in order to allow a proportional representation for each grade. However, it has finally been deemed a good approximation, to consider the total listed 19th century dwellings in Brighton, independently from the grade, as available population (at the risk of not finding any available participant from any grade II* and grade I because of their rarity). The results obtained for the grade II samples will be validated also for dwellings of the same period listed as grade I and II* because the grading does not imply any difference in the statutory regime. It is not feasible to apply any random statistic sampling either to this available population due to the uncertainties about the exact number of it as well as the actual accessibility of the properties. Therefore, case studies are being selected using a carefully balanced mixture of convenience and purposive sampling technique. A first selection has been done to find out potential participants who might be interested in this study, in order to be able to procure a number of accessible dwellings. An email was circulated within the University of Brighton mail system calling for all residents or owners of listed 19th century dwellings interested to take part in the study. This initial convenient sampling technique provided a set of accessible dwellings from which representative samples could then be selected. Purposive sampling will help then to limit the number of case studies or to decide which other ones to add, basing the choice on the knowledge of this population achieved by the researcher and validated through interviews and meetings with experts in this sector. To date 11 potential case studies are to be investigated; Figure 2 evidences their locations and Table 1 summarises their characteristics.

Figure 2: Map showing the location of the case studies selected at this stage
Table 1: Characteristics of the case studies selected

<table>
<thead>
<tr>
<th>Case study No.</th>
<th>Approximate Location</th>
<th>Typology and ownership info</th>
<th>Date of construction</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>First Avenue</td>
<td>Tenanted flat in converted house</td>
<td>2nd half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS2</td>
<td>Brunswick Place</td>
<td>Tenanted flat in converted house</td>
<td>1st half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS3</td>
<td>To be confirmed</td>
<td>Owned flat in converted house</td>
<td>2nd half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS4</td>
<td>Hanover Crescent</td>
<td>Owned terraced house</td>
<td>1st half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS5</td>
<td>Brunswick Place</td>
<td>Owned flat in converted house</td>
<td>1st half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS6</td>
<td>Russel Square</td>
<td>Owned flat in converted house</td>
<td>1820</td>
<td>II</td>
</tr>
<tr>
<td>CS7</td>
<td>Arundel Terrace</td>
<td>Owned flat in converted house</td>
<td>1st half of the 19th C.</td>
<td>I</td>
</tr>
<tr>
<td>CS8</td>
<td>Norfolk Terrace</td>
<td>Owned flat in converted house</td>
<td>1860</td>
<td>II</td>
</tr>
<tr>
<td>CS9</td>
<td>Grand Parade</td>
<td>Owned flat in converted house</td>
<td>1st half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS10</td>
<td>Roundhill Crescent</td>
<td>Owned flat in converted house</td>
<td>2nd half of the 19th C.</td>
<td>II</td>
</tr>
<tr>
<td>CS11</td>
<td>Sussex Square</td>
<td>Owned flat in converted house</td>
<td>1st half of the 19th C.</td>
<td>I</td>
</tr>
</tbody>
</table>

The case studies selected so far are, therefore, well distributed geographically throughout the city as well as historically within the 19th century and furthermore they contain a good mixture of owned and tenanted flats as well as grade II and grade I dwellings. Needless to say that owner-occupiers will have different incentives compared to tenants when it comes to any refurbishment interventions; this will be accounted for and factored accordingly at later stages of this study. For each of the selected case studies a desktop research is first conducted to collect and analyse data about the heritage value of the building and its specific fundamental features needing protection (Historic England 2011; Herman and Rodwell 2015).

5.3 Simulation

5.3.1 The simulation software

At this stage, the research methodology involves the use of energy dynamic simulations in order to identify the current energy consumption and carbon emissions for each case study. Simulation has been chosen as it has several advantages compared to a field test (Yang et al. 2014): it is less time consuming and less expensive compared to a field experiment; importantly, in case of buildings in-use, it is non-intrusive; factors like outside weather data can be controlled and changed in order to isolate the effects of occupancy alone as well as those of one retrofit measure or of a combination of them.

In order to make a decision concerning the simulation software to use, a literature search has been conducted together with a desk survey of the available data and conversations with experts in the sector. The research conducted so far gives good reasons to believe that either Energy Plus (Ascione et al. 2011; Olsen & Chen 2003; Pernigotto et al. 2012; Stazi et al. 2013; US Department of Energy 2015; Yang et al. 2014; Wei et al. 2014) or IES-VE (IES 2016; Ingram 2013; McNally 2014; Memon 2014; Moran 2013; Pomponi 2015; Yang et al. 2015) is a suitable software to be used in this study for modelling the energy efficiency of TLDs. IES-VE has been chosen because it is already validated by a number of studies, it allows the simulation of multiple case scenarios to be applied on the same model, hence the comparative analysis of the interventions. Furthermore, it is an application developed in the UK and its use is widespread in the country as well as around the world. It offers a more user-friendly interface and requires less coding skills than Energy Plus. However, unlike Energy Plus, it is not an open source (which can potentially introduce some limitations on more advanced coding in complex simulations) but this was not considered to be the case in this research.
5.3.2 Simulation stage 1: primary data collection and new data generation

The body of scientific research agrees in suggesting the importance of using empirical data in order to achieve a good similarity between the modelled and the monitored fuel consumption pertaining to space heating (Hong et al. 2006; Stazi et al. 2013). It is therefore fundamental to describe the building in-depth in its geographical location, shape, materials and construction, pattern of use (Ingram 2013; Panayiotou 2014) as a part of an in-depth multi-units of analysis multi-case study approach chosen for this study. Hence, a measured survey is being conducted for each case study and data concerning building typology, orientation, size and type of the openings, domestic appliances, materials of the envelope, are being collected. Secondly, as soon as the environmental conditions are suitable, a thermal-imaging survey of the envelope will be carried on. Data about the building services, the actual pattern of use, life style and temperature set points, retrofit interventions already executed in the dwelling, eventual hurdles faced to install them, are being gathered for each case study using a questionnaire to be filled by the participants and a follow-up interview conducted with them. The actual data relating to the real use of the building obtained from the questionnaires and interview, will replace the default values in datasets built in the energy performance simulation package to make sure that the results will be as close to the actual performance of the building as possible. Two data loggers (one in the living area and one in the bedroom area) will be placed in each case study, possibly for two consecutive winter months, to record the internal temperature and relative humidity in the dwellings. These data will be used as a checkpoint to quality control the information produced by the users.

The whole set of data collected will be inputted in the dynamic simulation software in order to predict, with a good degree of certainty, the current energy performance and carbon emission of each case study.

The use of case studies in this research presents an ideal opportunity to check the simulated energy consumption results against actual energy use data and therefore guarantees a higher reliability of the results generated though simulation of the intervention scenarios. For this purpose, the main household electricity and gas supply meter readings will be collected in each dwelling on a monthly basis for a period of one calendar year. Also, with permission of the residents, historic data could be collected from the relevant energy companies. The historic data, combined with an analytical review of seasonal meter reading, will help work out the share of energy use for space heating, hot water, cooking and appliances (Lloyd et al. 2008; Moran 2013). The results in terms of energy consumption achieved with the modelling will finally be checked against the data collected through meter readings (Ascione et al. 2011; Lomas et al. 1997; Moran 2013).

To allow comparison between the different samples, a second modelling phase of the buildings in their status-quo condition will be conducted within this stage, using a typical household with identical or similar pattern of use, temperature set-points and lifestyle for each of the case studies. The results achieved from this second round of simulations will constitute the benchmark to refer to when assessing realistic energy savings and carbon reduction potential improvements.

5.3.3 Simulation stage 2: evaluation, comparative analysis and assessment

To evaluate the approaches and common practices adopted in the refurbishment of this type of properties, part of the literature review that has been done, will be further developed and secondary data collection (concerning similar listed buildings’ consents already guaranteed in the area) will be carried out. The analysis of the data (concerning retrofit interventions already done within the dwelling and the hurdles eventually found) previously gathered from the questionnaires and interviews with the users, will aid in shaping the list of feasible interventions. Finally, semi-structured questionnaires will be sent to local
conservation officers and possibly a few interviews with them will take place. The combination of such methods will generate possible scenarios supported by the outcomes of this systematic analysis with an expert overview of the practicality of such measures to come up with the potential retrofit interventions on the selected listed buildings within the context of regulations and guidance.

This second stage of simulations will be again divided in 2 phases. The first one will aim to find out the impact of each possible intervention with reference to the historic fabric, energy consumption and carbon emissions for each of the dwellings. This will be done using the standard pattern of use, lifestyle and temperature set points used for the second phase of modelling within stage 1 in order to compare the results with those of the benchmark.

Finally, the economic aspect of any retrofit measure will be analysed and used to carefully weigh the interventions scenarios. Combinations of interventions will be selected and simulated within a final phase of simulations for each case study, in order to strike a sensible balance between performance improvements, conservation of historical/architectural values and cost implications of those solutions so that an overall feasible and sustainable approach to such measures can be taken.

6 Envisaged problems and solutions

6.1 Human factor
This research will use questionnaires and interviews to gather data concerning the lifestyle, pattern of use, temperature set points for each case study to replace those suggested by the simulation software. In case these data are not possible to obtain or not exhaustive, the approximate estimates as suggested by CIBSE guides (Butcher et al. 2015) and used for the second phase of simulations stage 1, will be adopted. A similar approach will be adopted for the meter reading in case the data collected was not inclusive.

6.2 Fabric factors
A consistent body of research currently agrees on the importance of a clear understanding of the construction of the building envelope, which is used primarily for heat loss calculations (Barnham et al. 2008; Heat et al. 2010; Ingram and Jenkins 2013; Jenkins 2008). The area of external wall can be the largest contributor to this (Ingram 2013). The IES-VE model that will be used requires the assessor to input construction details, and the software calculates the wall U-value based on thickness, conductivity, density, heat capacity and resistance of each material (Ingram 2013). However, research conducted by Glasgow Caledonian University for Historic Scotland (Baker 2008 2011) and by the Society for the Protection of Ancient Buildings (Rye 2010) has demonstrated how the U-values achieved with the standard calculation method used for modern constructions, are not representative of the actual values for traditional constructions. Instead, they frequently overestimate them, therefore underestimating the actual performance of the building. The previously cited research has been conducted in Scotland on typical traditional masonry stone buildings. However, the construction materials and techniques of the external walls in dwellings in the city of Brighton and Hove during the 19th century were certainly peculiar and not easy to assimilate to any modern envelope, made by homogeneous layers of different materials. The typical compound used in this area was called Bungaroush and was mainly used for garden walls and party and rear walls of terraced houses, although it is also found in the front elevations. The Regency Society describes Bungaroush as “made principally of lime, gravel, coarse sands and flints, often with some brick fragments or other rubble added. The combination forms a type of mortar, or reinforced concrete” (Regency
Society 2016). For this matter, it has also been considered whether or not to collect primary data from the real cases to calculate the U values of such a construction material using heat flux-meters coupled with internal and external temperature sensors (Baker 2008, 2011; Rye 2010). This could be an option which adds to credibility of the study but might not prove to be the most practicable as it will have cost implications and may involve more time or repeated visits which may not be welcomed by the participants. The contingency plan would be to calculate the average U-value for a layer of wall combined of Bungaroush components. This is not an easy task but it is not impossible to carry out. Furthermore, if the risk of using a calculated U-value for traditional buildings in this is to be overestimated (Baker 2008, 2011; Rye 2010), then the results obtained adopting it would still describe a scenario that sits on the safe side.

6.3 Technological factors

Researchers currently agree on considering the biggest uncertainty and simplification in any building energy simulation to be associated with the ventilation rate predictions (Hong et al. 2006). Air tightness of the dwelling is used in the energy assessment when determining the heat lost through infiltration. For the first stage of simulation, initially, average infiltration rates from the CIBSE Guide A, will be used (Butcher et al. 2015). The gap eventually found between the energy consumption as a result of simulation and the one deduced from the meter reading, together with the thermal-image analysis of the external envelope, could help (considering any case in its own context and specific settings) to calibrate the modelling, adjusting the assumptions about air leakage to be used in the software. The discrepancies between model and real scenario, remaining after these calibrations, if any, could be later applied to the results obtained from the modelling of the retrofit interventions on the selected dwellings.

7 Conclusions

Benbasat et al. (1987) believe that a clear description of data sources and the way they contribute to the findings of the research is an important part of the study that guarantees the reliability and validity of the findings. Therefore, the main aim of this paper is to illustrate the research framework specifically designed for this study, the methods of data collection, the qualitative and quantitative data to be collected; such methodology has been explained and graphically represented in one diagram (figure3) to help provide an overall understanding of the research design for this study. The research questions and objectives have defined the methods and approaches for data collection. The study could be divided in four phases, designed in line with the research objectives; these are set out to be fulfilled in sequence, using the combination of methods previously selected to gather, collate and analyse a comprehensive set of qualitative and quantitative data. In each subsequent step, the findings achieved in the earlier stage serve as a milestone for the following one and data previously gathered or generated are added to new datasets in the configuration of new feasible scenarios.

In the first phase, qualitative methods of data collection (questionnaire and semi-structured interviews) are used concurrently with quantitative ones and the qualitative data obtained from the interviews are quantified in order to become input variables in the first simulations set. Therefore the first stage uses an embedded concurrent mixed-methods design, which happens in the data collection and analysis. A form of sequential mixed methods also happens at this stage when quantitative data obtained from data logging are used to quality control the qualitative data previously obtained from the interviews and quantified to serve as input data in the simulation. A second set of simulations follows within this phase, where the quantified data obtained from the interviews are substituted by quantitative data obtained from secondary data collection in order to provide, from each
case study, quantitative results that can be compared. Finally, within the same stage, a sequential mixed-methods design takes place when quantitative data from the meter reading are analysed together with quantitative results from the simulation and qualitative data from thermal imaging to adjust the assumptions concerning air leakage.

In the second phase of this study, new qualitative data are collected making use of literature review, secondary data collection, questionnaires and semi-structured interviews with experts and these are analysed together with some of the qualitative data previously obtained from the interviews carried on during the first stage. As a result of such phase, qualitative data concerning potential interventions on the cases study selected, are gathered and analysed to give a qualitative output.

The third phase of research makes again use of a concurrent embedded mixed-methods design in which qualitative results from the previous phase are quantified to be inputted in a third stage of simulation together with the quantitative data obtained from the previous stage of simulations.

In the fourth phase of research, new quantitative data are provided making use of secondary data collection and are analysed together with the qualitative data from the second phase and the quantitative data obtained from the third stage of simulation in order to obtain new quantitative data to input in the last stage of simulation. Therefore this stage sees again a concurrent mixed-methods design happening in the data analysis. Concurrent mixed methods happens also finally in the discussion of the subsequent findings from the four stages.

With such carefully and comprehensively developed methodology, as discussed in this paper, the results of this study are expected to be contributing to support homeowners, tenants and stakeholders in the decisions involving energy upgrade measures for this part of the housing stock, thus decreasing the risk of non-cost-effective interventions and negative impacts on the heritage value. The methodology has been developed such that the study can take account of the performance of these buildings in their unimproved condition to assist the owners or tenants in diagnosing areas where energy savings could be made more effectively. Finally, previous research in this sector has highlighted the lack of local policies and guidance on these issues; the modular structure of this methodology also allows for repetition in identical or similar situations so that the outcomes can contribute to making policies or devising new regulations, guidance or incentives for local or central governments.
Figure 3: Framework of the research design
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COURTYARD ENVIRONMENTAL PERFORMANCE ANALYSIS OF YUNG HO CHANG’S SPLIT HOUSE

Hing-wah Chau ¹, Victor Bunster ² & Masa Noguchi ³

¹, ², ³ Faculty of Architecture, Building and Planning, The University of Melbourne,
¹ chauh@unimelb.edu.au, ² v.bunster@student.unimelb.edu.au, ³ masa.noguchi@unimelb.edu.au

Abstract: Yung Ho Chang is an influential contemporary Chinese architect. He is the founder of the Graduate Centre of Architecture at Peking University and was the Head of the Department of Architecture at the Massachusetts Institute of Technology. One of his most famous works is the Split House built in Beijing whose V-shaped layout aims to embrace an open courtyard. During the conceptual stage, Chang produced a series of diagrams to explore different geometrical configurations. This study aims to compare the performance of these different alternatives in order to assess whether environmental factors were addressed in their full potential. Accordingly, air-flow and shading analysis were conducted and contrasted against the performance of the final configuration. The importance of visualisation of such performance measures during early stages of the design process is also discussed.

Keywords: Contemporary Chinese architecture, Yung Ho Chang, air flow analysis, shading analysis, Split House
1 Introduction

Chinese architects acted as public servants in state-owned design institutes in the Mao era (1940-1976) and the post-Mao era in the 1980s, fulfilling national tasks and enforcing government policies. Since the implementation of the architect registration system in the 1990s, Chinese architects can now work independently, enjoying more freedom and individual expression. After the economic reform of Deng Xiaoping, the expanding middle class and emerging design-oriented developers encourage architects to carry out design experimentation. Some architects have responded to this shift through a demonstration of self-conscious practice and reflective thinking. Among them, Yung Ho Chang (b. 1956) is a prominent figure, who set up his private architectural practice in Beijing as early as 1993. His design strategies are shaped primarily by his cross-cultural exposure.

Chang’s cross-cultural exposure correlates with his family background and architectural education. He was brought up in a liberal family environment in Beijing, which allowed him to develop individual interests. Both his parents were good at English, and his father, Zhang Kaiji (1912-2006) was a famous architect responsible for the design of many landmark buildings in China, including the National Museum of Chinese History, Beijing (1959) and the National Art Museum, Beijing (1962). Since his childhood, Chang was frequently taken to see exhibitions and exposed to foreign pictorials and journals, which aroused his interest in drawing and fine art. Since his father did not have the opportunity to study abroad, he insisted that his two sons were well prepared for overseas study (Chang 2012: 11). Following his father’s advice, he studied architecture, enrolling at the Nanjing Institute of Technology (NIT), the same school as his father, in 1977, and went to the US for further study in 1981. Compared with his Chinese counterparts, Chang is a pioneer in many respects. He belonged to the first cohort of students who received local university education and overseas study opportunities after the ten-year Cultural Revolution (1966-76). He was the founding professor of the Graduate Centre of Architecture at Peking University, Beijing (1999), the first Chinese professor to be the Head of the Department of Architecture, Massachusetts Institute of Technology (MIT, 2005-10), and has been appointed as a jury member of the prestigious Pritzker Architecture Prize since 2012.

Chang lived in a traditional courtyard house in Beijing during his childhood until thirteen years old (He 2008: 62-63), which has a profound influence on his architectural design. Due to his obsession with Chinese courtyard houses (Ruan 2006: 118), the courtyard becomes one of the most recurrent themes in his work as exemplified in the Qingxi Hillside Housing Project (1995), the Morningside Centre for Mathematics (1998), and the Southwest China Bio-Tech Base (2001). The earliest study was his Courtyard House Projects (1991) demonstrating a strong preference for rational guiding principles of spatial and formal subdivision. Both Courtyard Houses 3 and 4 show a meticulous attention to proportion and are rigorously based on the symmetrical principle (Figs. 1 & 2), in which these two houses can be equally bisected and the Courtyard House 4 has a pair of building blocks on both sides of a linear courtyard.
Courtyard Houses 3 and 4 are theoretical projects without being realized. Both of them did not have any actual site location and, apparently, the architectural design of these two houses only involve pure aesthetic spatial subdivision and formal manipulation without considering its relationship with surrounding contexts and its orientation in response to climatic conditions.

The bisected form of the schematic Courtyard House 4 has been further elaborated in the subsequent Split House built in Beijing in 2002. The Split House is one of the residences at the Commune by the Great Wall in Beijing developed by SOHO China. Conceived as a generic modular concept, the Split House is designed to cope with various site conditions by adjusting the angle between the two blocks (Chan 2005: 130). The design concept behind is the adjustment of a flexible prototype, which can be adapted to other locations.
A total of eight different configurations were developed during the conceptual stage (Fig. 3). In Scenario A, the two building blocks are combined to form a single house. In Scenario E, they are joined together to form a long linear structure. Scenarios B and H show parallel arrangement with a linear in-between courtyard in resemblance to the previous Courtyard House 4 project. In Scenarios C and G, the two blocks are in V-shaped relationship, whereas in Scenarios D and F, they are perpendicular to each other. Depending on various site conditions and the actual needs of the client, the Split House can become a single house, a parallel house, a right-angle house or even a back-to-back house (Pearson 2004).
Among the eight configurations, Scenario C is adopted as the final disposition of the Split House. The two building blocks are connected together by the vestibule embracing the courtyard in the middle with living area on one side and dining area on the other side. (Fig. 4). According to Chang, the original idea was to “transplant the traditional courtyard house in Beijing from its dense urban context into the pristine landscape” (Pearson 2004: 95). Instead of fully enclosing the courtyard on four sides, one side of the courtyard directly opens to the landscape. This conveys a clear gesture to embrace the natural landscape by drawing the magnificent scenery into internal spaces and preserving the existing trees within the triangular courtyard.

By splitting the house into two wings at a forty-five degree angle, functions inside each wing can be effectively demarcated. An internal staircase is provided in each wing for accessing to the bedrooms above (Fig. 4). Staircases are strategically located on the inner side of each wing to act as a semi-private transitional circulation space. Spatial hierarchy is demonstrated with an open plan for living and dining areas on the ground floor, servant rooms behind the kitchen, semi-private staircases connecting the two floors, and more private bedrooms on the upper level.

When the former Courtyard House 4 and the subsequent Split House are compared, the arrangement for the upper floor plans are quite similar. Both designs have significant setback on both ends of the upper levels. In the Courtyard House 4, the first floor plan of each building block has a tripartite division with enclosed rooms in the middle portion. In the Split House, the tripartite proportion is no longer maintained but the indoor-outdoor relationship on the upper level is more clearly defined with direct access to roof garden from each bedroom.

During the conceptual stage, a total of eight configurations have been developed as mentioned before (Fig. 3), so the question is whether the current design can provide a comfortable courtyard environment for users. In this paper, the relationship between
different geometrical configurations of the building form and their air flow and shading performances are analysed. In order to facilitate the comparison, air flow diagrams and shading diagrams for different configurations are prepared to see whether these factors have been well addressed.

![Figure 5: The courtyard of the Split House](image)

2 Air Flow Performance

The courtyard is a traditional building form used by many civilisations all over the world (Muhaisen 2006: 245) and has been widely recognised as an environmentally responsive form (Ratti 2003: 54). People living in hot regions have attempted to deal with the issue of thermal comfort over the centuries through their vernacular architecture with the courtyard form. The relationship between the proportions of the physical parameters of the courtyard form and its associated air flow pattern has been investigated by many researchers such as Ok (2008) and Moosavi (2015). The major concerns are how to influence the wind speed through building geometry and to improve the comfort level of the living environment through natural ventilation, especially in hot and arid climates, which is quite different from the context of the Split House.

The Split House is located in Badaling, which is 65km to the north of Beijing CBD. The mean of maximum air temperature per month ranges from 31°C in July to -2°C in January and the mean of minimum air temperature per month ranges from 19°C in July to -15°C in January. According to the Wind Rose of Badaling, the mean wind speed per year is 14 km/h and the highest wind speed can reach 61km/h. The prevailing wind mainly comes from the north-west direction (Meteoblue 2016). Figure 6 compares air flow diagrams of different configurations of the Split House. Since Scenario H and Scenario B are quite similar, so only seven configurations from Scenarios A to G are compared.
Figure 6: Air Flow Diagrams of Different Configurations of the Split House
Taking the specific climate of Badaling into consideration with only a maximum of 31°C highest temperature in summer, it is important to orientate the Split House in a manner that can reduce the speed of airflows within the courtyard, especially during the cold winter time. Both Scenarios D and E are very effective in reducing the wind speed in the courtyard against the strong wind coming from the north-west direction. This is in line with the findings of Sharples & Bensalem (2001) as both scenarios have a main façade to be positioned in perpendicular to the wind direction.

From the air flow perspective, the adopted configuration of Scenario C may not be the optimum arrangement. In fact, the air flow at the junction of the V-shaped building blocks reach a higher speed. The wind speed in the courtyard cannot be effectively reduced through the building configuration. If the V-shaped relationship of the two building blocks has to be maintained, an alternative disposition can be considered by having a façade facing in perpendicular to the wind direction (Fig. 7). This can achieve a lower wind speed in the courtyard compared with Scenario C.

![Image of Air Flow Diagrams of an Alternative Scenario of the Split House](image.png)

Figure 7: Air Flow Diagrams of an Alternative Scenario of the Split House

3 Shading Performance

Similar to the air flow analysis, shading performance of the courtyard has attracted the attention of many researchers, such as Mohsen (1979), Muhaisen (2006) and Yasa (2014). Most of these studies examined the geometrical parameters of courtyard forms in hot climate and discussed how the courtyard could be shaded from intense solar heat gain to achieve the thermal comfort of the environment as the absorbed solar radiation can increase the surface temperature of the courtyard. As mentioned by Mohsen (1979: 90), the building orientation is an important factor in controlling heat gain. Muhaisen (2006: 1050) also states that whether the courtyard is shaded or exposed to the sun depends on the position of the sun and the geometry of the form. A proper configuration of the courtyard can ensure adequate solar heat gain in winter for warming up the space and providing sufficient shading in summer to reduce the need for cooling.

In the case of the Split House, the situation is different from those courtyard forms in hot climate. In Badaling, the winter can be as low as -15°C and the highest temperature in the summer is 31°C, so it is crucial to maximise the solar heat gain during the winter in addition to provide shading during the summer. As the winter solstice is on 21 December and the summer solstice is on 21 June, Figures 8 and 9 compare shading diagrams of different configurations of the Split House on winter solstice and summer solstice respectively.
Figure 8: Shading Diagrams of Different Configurations of the Split House on Winter Solstice (21 December)
Figure 9: Shading Diagrams of Different Configurations of the Split House on Summer Solstice (21 June)
As shown in Figure 8, both Scenarios B and G have the longest shading period during the winter, which is not desirable under cold weather. Comparatively, the adopted configuration of Scenario C has the least shading period for the courtyard among the seven configurations, which is a favourable option during the cold winter. If the V-shaped relationship of the two building blocks has to be maintained, an alternative disposition can be considered by orienting the courtyard directly facing the south direction. This can maximise the solar heat gain as shown in Figure 10.

![Figure 10: Shading Diagrams of an Alternative Scenario of the Split House on Winter Solstice (21 December)](image)

Since the summer time of Badaling can still reach up to 31°C, it is still desirable for the building form to have some shading performance for the courtyard. As shown in Figure 9, the adopted configuration of Scenario C provides some shading for the courtyard, but is not as good as Scenarios B and G, which have longer shading period.

4 Conclusions
This paper aims not to identify the optimum arrangement for the Split House nor to thoroughly quantify the impact of air flow and shading performance on the interior spaces of the house. Instead, through the use of the Split House as a case study, the importance of visualising the relationship between the building form and different environmental parameters, such as the air flow and shading factors, is illustrated. Since the courtyard geometry and house massing have a significant impact on the air flow and shading performances, visualisation since early stages of the design process can be a useful approach to identify the possibilities and limitations of different layout and site planning alternatives towards making informed design decisions. Although only two factors (i.e. air flow and shading) are discussed in this paper, more comprehensive approaches to environmental performance analysis and visualisation focused on further environmental parameters may provide critical information to pursue desirable and comfortable living ambiances for dwellers.

References


OVERHEATING AND DAYLIGHTING IN LONDON’S TALL RESIDENTIAL BUILDINGS; AN OPTIMISATION QUEST

Bachir Nebia¹, Kheira A. Tabet Aoul²

¹ Roberts & Treguer Ltd, London, United Kingdom, bachir.nebia@gmail.com
² Architectural Engineering Department, United Arab Emirates University, UAE, kheira.anissa@uaeu.ac.ae

Abstract: In dense cities such as London, the housing shortage is far from being solved and the number of highly glazed tall residential buildings is increasing at a high rate. With the desire to vertically densify London, apartments in high-rise residential buildings are at a different exposure to the external environment. Depending on their floor level and orientation, the apartments may experience different levels of thermal and visual comfort. The objective of this paper is to build a simplified tool able to predict the internal temperatures and the daylighting level, and a design comparative tool that focuses on the rapid assessment of overheating risk and daylight performance in tall residential buildings. This paper addresses the issue by comparing different design variables of a single and double-sided flat in a high rise city based building, by changing the density of heat transfer, the thermal mass, the ventilation strategy and the orientation. Using Integrated Environmental Solutions Virtual Environment (IES VE), temperature and daylight factor measurements are used to create a parametric comparison tool to appraise the impact of each variable on the overheating risk and daylighting performances, and to generate a simplified tool to predict the internal temperatures and the average daylight factor. Results show that apartments, which are more exposed to the weather, because of their floor level or orientation, are more susceptible to overheat in the summer while exceeding the daylighting recommendations and vice versa. Therefore, there is a need to consider different design strategies at different level and orientations of a high-rise apartment building. Simple and practical design strategies, such as an appropriate ventilation system or an appropriate glazing ratio following the floor level of the apartments, could be adopted to mitigate the overheating risk and meet an appropriate daylighting level in the actual and future weather scenarios in London.

Keywords: Tall Residential Buildings, London, Overheating, Daylighting, Comfort, Mitigation & Adaption
1 Introduction

The building sector in the UK generates 35% of the total CO2 emissions and the residential buildings represent 65% of it (Salisbury et al. 2013), becoming the targeted sector to achieve the UK carbon reduction plan. One of the main decisions taken by the UK government is the Zero Carbon target for all new dwellings by 2016 (McLeod, Hopfe & Rezgui 2012). Following the latest predictions, London is expected to be home to more than 10 million people by 2030 (New London Architecture & GL Hearn 2015) carrying critical housing demands. Tall residential buildings are considered one of the solutions to meet the challenge of the rapid demographic increase. The London Tall Buildings Survey (2015) indicates that 81% of the high-rise buildings under construction in London are for residential purposes. However by taking into consideration the vulnerability of the capital and the forecasted temperatures increase in the UK, adaptations strategies are becoming more and more important to cope with this changing climate. Studies have shown that highly insulated buildings may be at overheating and discomfort risk (Coley & Kershaw, 2010), (Arup Research + Development, Bill Dunster Architects 2005).

Additionally, given that organisations such as the Zero Carbon Hub or NHBC are providing guidance to mitigate the overheating risk using practical and simplistic design strategies, the actual study is taking into consideration both mitigation and adaptation approaches in residential buildings in London.

Further, some residential archetypes such as high-rise residential buildings seem to be at a higher risk of overheating (Melissa Taylor 2014), with the top floor apartments being more vulnerable to thermal discomfort risks than lower ones. The relationship between the floor position of the apartments in the building and the overheating risk is not clear. Hence, the aim of this study is to explore this relationship by assessing the overheating risk in a high-rise residential building. Additionally, an investigation on the relation between daylighting and thermal comfort will be useful to determine a balanced design solution. Other design parameters such as the ventilation have been explored, however for the purpose of this paper the results won’t be displayed.

The target solution of this study is to achieve, a simplified tool to predict both the internal temperatures and the daylighting level, and a design comparative tool that focuses on the rapid assessment of overheating risk and daylight performance in high rise-residential buildings. These will be useful for the industry to better understand the overheating risk in high-rise residential buildings and to help designers to avoid thermal discomfort and meet daylighting levels at an early design stage.

2 Research methods and tools

2.1 Benchmarks

The CIBSE Guide TM52 (2013, p.10) explained that “all comfort standards have problems, because they try to give precise definitions when the phenomenon they are describing is inherently imprecise.” The data from the simulations will be reviewed by both the CIBSE benchmarks and the EN15251 method. For the bedrooms a lower comfort temperature associated with sleeping will be used, 26°C for the CIBSE threshold and the Cat I for the adaptive methodology. For the living room a higher comfort temperature will be considered to assess overheating, 28°C and Cat II for CIBSE and EN15251 respectively.

In the current building regulation of the UK there is no specific requirement for daylighting in dwellings. However, the Approved Document Part L (2013) and Code for Sustainable Homes advise designers to follow closely the guidance given by the BS 8206-2 Code of
practise for daylighting (2008). Therefore, a special consideration should be given to the size of windows and glazed area to provide adequate level of daylighting and control solar gains to avoid overheating. The BS 8206-2 (2008) set minimum average daylight factor for different spaces in dwellings. 1%, 1.5% and 2% daylight factor for the bedrooms living rooms and kitchens respectively.

2.2 Modelling method

The model is based on a real building in the city of London that has been provided by one of the biggest engineering company in the UK, representing a typical high-rise residential building. Its properties are associated with the best practise for new residential buildings. The Integrated Environmental Solution (IES) Virtual Environment (VE) software is chosen as the dynamic simulation tool and the prevailing one for this type of investigations.

2.2.1 Building Geometry

The building geometry is representative of a simplified high-rise building incorporating the main characteristics of a typical high-rise residential building. The model has been validated, using floor layouts of an existing high-rise residential tower in the city of London. Appendix 1 illustrates the layout used for the model. The simulated apartments will be modelled between two similar floors. The total floor area of the apartments varies between 60 to 70 sqm. The orientation, the glazing ratio and the shading from the adjacent buildings will be considered as variables. The table and figure 1 illustrate the variable solar radiation at different floor levels.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>S.R at 0% shaded (kWh/m².a)</th>
<th>S.R at 25% shaded (kWh/m².a)</th>
<th>S.R at 50% shaded (kWh/m².a)</th>
<th>S.R at 75% shaded (kWh/m².a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat position: Top floor</td>
<td>Flat position: Middle top floor</td>
<td>Flat position: Middle bottom floor</td>
<td>Flat position: Bottom floor</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>360</td>
<td>320</td>
<td>190</td>
<td>130</td>
</tr>
<tr>
<td>East</td>
<td>590</td>
<td>455</td>
<td>260</td>
<td>180</td>
</tr>
<tr>
<td>South</td>
<td>750</td>
<td>560</td>
<td>360</td>
<td>185</td>
</tr>
<tr>
<td>West</td>
<td>560</td>
<td>440</td>
<td>270</td>
<td>150</td>
</tr>
<tr>
<td>A.S.H (m)</td>
<td>0</td>
<td>12</td>
<td>17</td>
<td>33</td>
</tr>
</tbody>
</table>

Figure 1: left: Solar radiation in each orientation (North, East, South, West) and at each flat position (Bottom, Middle Bottom, Middle Top, Top). Right: Flat position illustration

2.2.2 Construction

The building fabric and its thermal properties are primordial to the overheating investigation in dwellings. There is a considerable need to reduce the energy consumption for the space heating demand. Consequently, a super insulation strategy will be used for
the study. The thermal performance of the models will follow PassivHaus standards, which represents an improvement of around 40% from the 2010 England & Wales Building Regulations. The thermal properties used for the models are resumed in table 2. A lightweight (60 kJ/m².K) and a medium weight (140 kJ/m².K) thermal mass will be studied.

<table>
<thead>
<tr>
<th>Construction Elements</th>
<th>U-values (W/m²K)</th>
<th>g-value</th>
<th>Glazing lighting transmittance</th>
<th>Window frame factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>0.85</td>
<td>0.6</td>
<td>0.7</td>
<td>30</td>
</tr>
</tbody>
</table>

For the daylighting simulation, the 70% reflectance for the walls was considered, representing an approximation for a typical light colour reflectance.

2.2.3 Internal heat gains

The CIBSE Guide A (2015) was used for all the data for internal heat gains in dwellings. Three groups of internal heat gains, occupants (young couple with one child), lighting and appliances, were modelled on the dynamic simulation software.

2.2.4 Ventilation & building services

For the purpose of this study the space heating system is modelled in the cold months (October-April) with a set-point temperature of 20°C. The summer month will be excluded. Mechanical ventilation will be used at first for more sensible comparisons. The dynamic simulation will account for two types of air transfer, the mechanical air supply and the uncontrolled infiltration. The infiltration will be modelled as a fixed flow rate (0.25 ach), which will be defined depending on the volume of the modelled spaces. Based on the concept of a balanced dwelling, the mechanical ventilation will extract and supply at an equal flow rate. The extract will be from the wet rooms (bathrooms and kitchens) and the supply from the dry rooms (living rooms and bedrooms). The heat recovery (HR) system will be modelled with a summer by-pass system.

As regulated by the Approved Document F (DCLG 2010a) the mechanical ventilation will be modelled with two ventilation rates. The first one is the background, which will be maintained at a constant flow rate in relation to the occupancy of the apartments and the boost feature, which is modelled to permit purge ventilation at late afternoon if there is an increase in heat gains. It will also be considered in bedrooms for night purging when the internal temperature exceeds the comfort temperature and when the external temperature is below the internal one but not exceeding 10°C difference.

Natural ventilation was considered in a second set of simulations to mainly assess the difference between the potential ventilation of both typologies (single & dual aspect) and to compare the effectiveness of both natural ventilation and mechanical ventilation strategies to avoid overheating.

The bulk airflow will be simulated based on the differences in pressure across the operable windows and the equivalent orifice area. The operable windows were modelled with an openable area of 20% and a maximum angle of 10°. Following the MacroFlo Calculation methods (IES 2011), it corresponds to 0.34 discharge coefficient. Consequently, the equivalent orifice area is given by the same documents as almost 11% of gross area. In addition, as the position of the flats represents the main variable for the investigation of this study, the exposure type of the openings will change depending on the position of the
flats in the building. It will adjust the wind pressure coefficient in relation to the degree of
sheltering of the surrounding buildings.

It is very important to simulate as realistically as possible the opening pattern of the
operable windows and model it in accordance with the occupancy profiles of the
apartments. In brief, the windows will operate in the early morning, late afternoon and
evening for the living room, and for the bedrooms the openings will be used mainly for
night purging. The windows of the bedrooms and the living rooms are designed to open at
an internal temperature of 26°C and 28°C respectively only if the external temperature is
lower than the internal one. The internal doors will be modelled to remain open.

2.2.5 Weather data
The dynamic simulations will be carried out using the “control” weather file published by
the PROMETHEUS project for the current climatic conditions in London Islington. The
London Islington location have been chosen mainly because it represents an urban area
which has a low green space density and a high Land Surface Temperature (LST) (Zero
Carbon Hub 2015). In addition, for the climate change impact investigation, each
simulation will be repeated with a projected TRY for 2030, 2050 and 2080 with high
emission scenario (a1fi) at 90th percentile probability. Even if the DSY weather files has
been designed especially for the overheating studies, TRY weather files represents a more
appropriate data for this investigation (Coley, Kershaw & Eames, 2012).

2.3 Variables
The simulation study is based on a single reference building and a set of variables. The
reference building is an existing project in the city of London. The high rise-residential
building contains single and dual aspect apartments at different orientations. All flats were
assumed to have a high level of insulation modelled with both mechanical and natural
ventilation strategy. The floor location of the apartments in the building was the main
variable targeted in the hypothesis. To support the study, variation in the orientation, the
thermal mass and the glazing ratio are taken into consideration in the actual and future
weather scenarios. Table 3 summarises these variables. It should be also noted that in a
real context, the design process is more complex and might be different from the
assumptions taken in this study and might consider other variables and alternative design
parameters.

<table>
<thead>
<tr>
<th>Variables</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typology</td>
<td>Floor Position</td>
<td>Orientation</td>
</tr>
<tr>
<td></td>
<td>Single sided</td>
<td>Bottom floor</td>
<td>North</td>
</tr>
<tr>
<td></td>
<td>Double sided</td>
<td>Middle bottom</td>
<td>East</td>
</tr>
<tr>
<td></td>
<td></td>
<td>floor</td>
<td>South</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle top floor</td>
<td>West</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Top floor</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Thermal Mass</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glazing ratio</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>F</td>
<td>Ventilation</td>
<td>Mechanical</td>
<td>Natural</td>
</tr>
<tr>
<td>G</td>
<td>Weather</td>
<td>Control</td>
<td>TRY 2030</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TRY 2050</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TRY 2080</td>
</tr>
</tbody>
</table>
3 Results
The investigation of the study is mainly looking to one parameter, which is the floor level of the flats in a high-rise residential building. The four position variables (Bottom, Middle bottom, Middle top, Top) as shown in Figure 1, will be applied to all the simulations and will be constantly present in the analysis. As explained, further variations have been explored including the glazing ratio, the thermal mass, orientation, ventilation and weather data.

3.1 Comparison of the CIBSE benchmark and the EN 15251 threshold
A notable point from the left figure 2 is the variation between the overheating assessment by the CIBSE and the EN 15251 benchmark. The difference between the two methodologies is that the CIBSE threshold shows a lower trend for the overheating quantification. The right figure 2 shows the CIBSE benchmark for living rooms, which is higher than the Cat II EN 15251 threshold almost all the year. Using the control weather file, it seems that there is a significant difference between the two overheating assessment methodologies.

![Figure 2: left: Mechanically ventilated south low thermal mass 40% glazing ratio, living room overheating Hours. Right: Daily mean temperature and both adaptive and fixed overheating benchmark [London, Islington, control TRY]](image)

3.2 Impact of Floor levels
The figures 3 show separately the overheating assessment and the daylight factor analysis for a south living room at different floor levels and variable glazing ratios. Given the change to the flat floor level, it is notable that both daylight factor and the hours above the thermal benchmark have an increasing trend from the bottom to the top floor.

![Figure 3: In the left the number of hours above the benchmark and in the right the daylight factor for the mechanically ventilated south living rooms with low thermal mass at 40%, 60% and 80% glazing ratio [London, control]](image)
By combining the figures 3, the figure 4 illustrates a cross-purpose issue between daylighting and thermal comfort. At top level the daylight factors for the 40%, 60% and 80% glazing ratio are exceeding the BS 8206-2 recommendations. However, the hours above the thermal benchmark are significantly higher than the CIBSE threshold. For the bottom position, it is the opposite, while the living rooms are meeting the thermal comfort benchmark; the daylight factors are at their lowest values.

Figure 4: Number of hours above the benchmark and the daylight factor for the mechanically ventilated south facing living rooms with low thermal mass at 40%, 60% and 80% glazing ratio [London, Islington, control]

One of the main observations is that higher floor levels, which mean a greater solar exposure, result in higher overheating risks. In addition, an increase in glazing ratio is raising the hours above the overheating benchmark. Consequently, an increase in both parameters could represent a significant threat to the internal thermal comfort. In terms of design optimisation, finding the right solution that meets both thermal comfort and daylight is challenging. For some flat positions it is very difficult to meet both of them. As it can be seen from the figure 4, that the bottom positions have very low daylight factors, which do not meet the BS 8206-2 recommendations. Even if it is meeting the overheating requirement the low daylight factors in the bottom positions represent one of the consequences of the vertical urbanisation.

Looking at more details, the left figure 5 shows the temperature variation of 3 days where the flats are exceeding the benchmark and the external temperature is peaking at almost 30°C. A significant temperature difference can be observed between the same living rooms at different floor levels. The results of the internal temperature gathered from the simulations show that the highest living rooms are at higher internal temperature variation than the lowest ones. Even with a higher ventilation rate to mitigate the thermal discomfort risk, the increase in solar gains, caused by the reduction in shading, builds up heat internally and worsens the thermal comfort.
The same have been observed in right figure 5. Increasing the glazing ratio raises the overheating risk by allowing a higher conduction and solar gains, which in return turn on more frequently and at longer time lapse the boost feature of the mechanical ventilation system to cool down the internal spaces during the occupied hours.

3.3 Impact of Orientation

In urban dense high-rise residential buildings, the apartments are expected to face one single direction. Given the same environmental conditions, the internal environment may react differently depending on its orientation. It can be observed from the left figure 6 that the north facing living rooms are at lower overheating risk than the other orientations and that the South facing living rooms represent the most thermally uncomfortable spaces. In addition, the daylight factor results illustrated in right figure 6 shows that the North and East facing living rooms have a higher daylight factor than any other orientation and that the west facing living rooms have the lowest daylight factor. The orientation plays an important role in the cross-purpose relationship between the daylighting and thermal comfort. For example, it can be seen that for the north orientation it is easier to meet the daylight factor while having a low number of hours above the benchmark. At the opposite, for the west facing bedrooms it is much more difficult to meet the Code for Sustainable Homes recommendations while avoiding overheating.

The figure 7 shows the solar gains and the resultant dry temperature with the internal people heat gains illustrating the occupancy pattern. For the south facing living rooms, the peak in solar gains is occurring during the non-occupied period. The solar gains are...
intense and the internal temperature increases rapidly during the beginning of the afternoon, which makes it more difficult for the ventilation to mitigate the overheating risk. Regarding the west and east orientation, the peak of solar gains is closer to the late afternoon and morning occupied hours respectively. The difference between both orientations is that the west facing living room suffers more from the heat stored during all the day, which impacts on the internal temperature during the late occupied hour. The evidence shown here explains the cause of a high number above the benchmark of the south and west facing living rooms. The build up heat during the day due to the heat gains increases the internal temperature and worsens the thermal comfort.

Figure 7: Resultant dry temperature, Solar an internal gains for the low thermal mass living rooms at middle top position at 60% glazing ratio for the North, East, South and West facing [London, Islington, control].

3.4 Ventilation strategies
Throughout the simulations, both natural and mechanical ventilation strategies have shown their effectiveness to reduce the overheating risk. However, for the apartments that are more exposed to the solar radiation, natural ventilation seems to be more effective and helps reduce the overheating risk. As an example, the figure 8 illustrates a comparison between the mechanically and naturally ventilated south facing living rooms. For the top position the hours above the benchmark for the naturally ventilated living room is nine times less then the mechanically ventilated one. A considerable reduction is noticed when using natural ventilation strategy. However, in London some environmental conditions, such as noise and pollution level, may prohibit the occupants to open the windows to allow the exhaust of the additional heat in the internal environment.
Figure 8: Number of hours above the CIBSE benchmark for both naturally and mechanically ventilated south facing living rooms with low thermal mass and 60% glazing ratio [London, Islington, control].

The model has been designed in such a way to allow cross ventilation to occur in dual aspect flats and hence enable airflow to cross from a space to another. It can be observed from the figure 9 that the dual aspect flat provides a higher flow rate, which means a quicker purging capacity. This is impacting the internal temperature. It can be seen that in late afternoon the living room in the dual aspect flat has a lower temperature. Therefore providing cross ventilation might help reducing the number of hours above the benchmark.

Figure 9: Resultant dry temperature and air flow rate for both dual and single aspect flat, west facing living rooms with low thermal mass at 60% glazing ratio and top position [London, Islington, control].

3.5 Impact of Climate Change

The figure 10 corporates the result from four different climate weather files for the south facing living room. A sharp increase has been observed between the control weather file results and the 2080 TRY a1f1 at 90th percentile. In addition, it shows the considerable difference between the fixed CIBSE threshold and the adaptive model when assessing the overheating. By taking in consideration the capacity of humans to adapt, the EN 15251 Upper limit demonstrates a much lower overheating risk. However, it should be noted that even if the adaptive comfort shows a lower rate, there might be a limit for the human adaptation in future climates (Zero Carbon Hub 2013).
3.6 Summary of the results

The figures 11 and 12 illustrate scatter plots of the average internal dry temperature during the occupied hours from May to September and the figure 13 shows a scatter plot of the average daylight factor. By using the data illustrated in these figures, a multivariable linear regression methodology has been used to create formulae that help predicting both the average daylight factor and the internal dry temperature during the hottest months depending on the ventilation strategy, the orientation of the flat, its position in the building, its glazing ratio and its thermal mass. Therefore, by plotting the data of the variables, it is possible to predict both the thermal conditions using the equation 1, 2 and the Daylighting performances using the equation 3. The formulae will help predicting the internal thermal and visual conditions, which is useful to compare and assess the effectiveness of several strategies and design variables.

Figure 11: The average internal dry temperature for all the mechanically ventilated flats during the occupied hours from May to September [London, Islington, Control]

\[ T_{\text{av.in(occup)}} \approx -3.87 \times 10^{-6} \chi + 7.66 \times 10^{-3} \lambda + 2.55 \cdot \varphi - 2.63 \times 10^{-3} v + 18.65 \]
Equation 1 | The average internal dry temperature during the occupied hours of the hottest months for the mechanically ventilated flats. Where:

\[
T_{av.in(occup)} := \text{Average internal temperature during the occupied hours, [May-Sep] (C)}
\]

\(\chi\) : Orientation, The yearly vertical solar radiation of the flat’s orientation (kWh/m\(^2\).a)

\(\lambda\) : Position, The yearly vertical solar radiation on the flat’s facade (kWh/m\(^2\).a)

\(\varphi\) : The window / wall glazing ratio of the flat (%)

\(\nu\) : The thermal mass of the flat (kJ/m\(^2\).K)

Figure 12: The average internal dry temperature for all the naturally ventilated flats during the occupied hours from May to September [London, Islington, Control]

\[
T_{av.in(occup)} \approx -1.06 \times 10^{-6} \chi + 7.26 \times 10^{-3} \lambda + 3.26 \varphi - 6.80 \times 10^{-4} \nu + 18.51
\]

Equation 2 | The average internal dry temperature during the occupied hours of the hottest months for the naturally ventilated flats. Where:

\[
T_{av.in(occup)} := \text{Average internal temperature during the occupied hours, [May-Sep] (C)}
\]

\(\chi\) : Orientation, The yearly vertical solar radiation of the flat’s orientation (kWh/m\(^2\).a)

\(\lambda\) : Position, The yearly vertical solar radiation on the flat’s facade (kWh/m\(^2\).a)

\(\varphi\) : The window / wall glazing ratio of the flat (%)

\(\nu\) : The thermal mass of the flat (kJ/m\(^2\).K)

Figure 13: The Daylight Factor for both naturally and mechanically ventilated apartments [London, Islington, Control]
\[ DF \approx -1.92 \times 10^{-3} \chi + 6.01 \times 10^{-3} \lambda + 2.67 \varphi - 1.32 \]

Equation 3 | The Daylight Factor formula for both naturally and mechanically ventilated apartments

Where:

\( DF \): Average Daylight Factor (%)

\( \chi \): Orientation, The yearly vertical solar radiation of the flat’s orientation (kWh/m\(^2\).a)

\( \lambda \): Position, The yearly vertical solar radiation on the flat’s facade (kWh/m\(^2\).a)

\( \varphi \): The window / wall glazing ratio of the flat (%)

4 Discussion

With a dense typology, high-rise residential buildings suggest that the flats might face one single orientation, which is problematic in terms of solar gains, as each flat will have a different intensity of solar gains at a different time-lapse during the day. This also prohibits some flats to benefit from cross ventilation strategies. In addition, the modelled apartments have a small floor area, which is representative of the current industry in the UK. This doesn’t help in terms of thermal comfort because of a higher internal heat gains density (per/m\(^2\)) from the equipment, people and lighting, resulting in a higher risk of overheating. Additionally, the dense urban location of the high-rise residential buildings makes the design process much more challenging. Depending on the floor level and the orientation, the apartments might be under the impact of a relatively significant reduction in solar radiation (Wh/m\(^2\)) due to the shading from adjacent buildings.

The main focus of this study was the relationship between the floor levels of the apartments and their thermal and daylighting performances. In addition, the cross-purpose relationship between the daylighting and the overheating performances has been evaluated. As a solution to improve the daylighting performances, increasing the glazing ratio will enhance the daylight factor, however, it will also worsen the thermal comfort and vice versa. Increasing the thermal mass or providing a higher rate of purge ventilation might be the solution to mitigate the overheating risk while improving the daylight factor by increasing the glazing ratio. Further design solutions could be investigated to improve the thermal comfort and avoid overheating. For examples, Phase change Materials or new glass technologies might bring additional design solutions.

The potential to reduce the overheating risk through an effective ventilation strategy has been mentioned and tested for both natural and mechanical design solutions, in agreement with similar studies (Coley, Kershaw & Eames, 2012). Further, the results show that the purge ventilation at late afternoon and night is successful to mitigate the overheating risk. The difficulty lies on the appropriate choice of ventilation strategy that works in a real context. Tall residential buildings suggest a higher wind speed at the top levels, which is considered as an additional potential for natural ventilation. However, their urban and dense location might significantly reduce the airflow and impact the wind direction. Additionally, in big cities such as London, the level of air pollutants and the noise level could represent an additional barrier for the implementation of passive ventilation design strategy.

Due to the increasing urban densification, the city-based high-rise residential buildings are exposed to a more intense Urban Heat Island effect (Ismail & WanMohd 2012). It is recognised as a growing concern for dense cities such as London, which might reduce the effectiveness of the purge ventilation systems at night (Mavrogianni et al. 2011). Additionally, the predicted increase in temperatures due to the climate change might worsen even more the situation. Under the worst-case predicted scenario, the internal thermal comfort is highly threatened. With high external temperatures, the effectiveness of the ventilation to mitigate the overheating risk will be significantly reduced.
5 Conclusion

The main outcome from this investigation is that top-floor apartments associated with early or late afternoon solar gains are more susceptible to overheating than others, while easily meeting the daylight recommendations. Nonetheless, by adopting the appropriate design strategies depending on the floor level and the orientation, the daylight factor and thermal comfort could be met to some extent. Limiting solar gains in the summer, controlling internal gains, providing an effective ventilation strategy and designing appropriate glazing to wall ratios are the key to maintain the internal environment at thermally and visually comfortable conditions. In addition, the multivariable regression analyses carried out from the simulations results has led to simplified formulae that help predict the average internal temperatures during the hot season by simply plotting design parameters, such as the ventilation strategy, the orientation, the glazing ratio, the thermal mass and the position of the flat. This could be very useful as a design guideline at the early design stage.

Finally, knowing that 212 tall residential developments have been proposed in London in 2015 (New London Architecture & GL Hearn 2015), which represents more than 80% of the high-rise developments proposed, this paper could be the beginning of an extensive work with an aim to develop overheating and daylighting requirements that could be used to improve the existing building regulations for new high-rise residential buildings in UK. For that further research could be done on different residential building typologies using different geographical location to cover the whole residential building stock in the UK.

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Appendix 1 | Floor layout of the modelled apartments
HOUSEHOLD AIR POLLUTION IN DEVELOPING COUNTRIES: A REVIEW OF HEALTH IMPACTS ON WOMEN AND CHILDREN

Neveen El Bendary¹ & Hasim Altan²

¹ Sustainable Design of the Built Environment, Faculty of Engineering & IT, British University in Dubai, UAE, bendary_n@yahoo.com
² Department of Architectural Engineering, College of Engineering, University of Sharjah, Sharjah, UAE, hasimaltan@gmail.com

Abstract: Indoor Air Pollution or Household Air Pollution (HAP), a term that is more precise in considering the source of pollution, is dated back to the prehistoric era where humans began using fire inside shelters for heating, cooking, and lighting, the soot traced in prehistoric caves is an evidence of high levels of indoor air pollution. World Health Organization (WHO) indicated that 50% of the world population, almost all in developing countries, use solid fuels in the form of coal and biomass. Thus, household Air Pollution (HAP) has been correlated with poverty as families in the unprivileged areas struggle to meet their daily household energy needs for cooking, lighting, and heating. Sources of household energy in the developing countries vary according to environmental influences and types of populated places. Household solid fuels are mostly used in poor developing countries while fuel-wood is used in developed countries for heating purposes. Household socio-economic condition determines the fuel type used in household activities and the burning efficiency. Fuel type and burning efficiency are important factors to control household air pollution and health outcomes. Studies proved the link between household air pollution and the household socio-economic status. This study is investigating the relationship between household air pollution in developing countries and the adverse health impacts on children and adults, mainly women, and the adverse birth outcomes. The paper is based on extensive literature review from recent scholar articles and journals with reference to WHO guidelines and information. Accordingly, HAP from solid fuel combustion, mainly for cooking, is the main global health threat today causing 4.3 million premature deaths worldwide annually, and evidence of adverse health outcomes are proved to be correlated with exposure to HAP while the exposure is recorded to be higher in women and children under five years. Therefore, it is essential to provide global access to alternative clean resources of energy to avoid millions of deaths and develop the health of billions of people. There is a majority of low-income households in rural areas that count on free biomass fuel, which makes it challenging to implement intervention strategies comparing with rural areas where the population is paying for the solid fuel. Moreover, successful intervention strategies must consider the socio-economic status of the targeted population.

Keywords: Household Air Pollution, Indoor Environment, Women’s Health, Sustainable Interiors, Children Health.
1 Introduction

Indoor Air Pollution (IAP), or Household Air Pollution (HAP), a term which is more precise in considering the source of pollution (Reid et al. 2012); is dated back to the prehistoric era once man started using fire inside shelters for heating, cooking, and lighting, the soot traced in prehistoric caves is an evidence of high levels of indoor air pollution. According to WHO, 50% of the world population, almost all in developing countries, use solid fuels in the form of coal and biomass.

Household air pollution has been correlated with poverty, as families in the unprivileged areas struggle to meet their daily household energy needs for cooking, lighting, and heating. Sources of household energy in the developing countries vary according to environmental influences and types of populated places (Martin 2012). Household solid fuels are mostly used in poor developing countries; however, fuel-wood is used in developed countries for heating purposes (Sood 2012). Furthermore, household socio-economic condition determines the fuel type used in household activities and the burning efficiency. Fuel type and burning efficiency are important factors to control household air pollution and health outcomes (Fig. 1). Studies proved the link between household air pollution and the household socio-economic status, as households in high-income and educated settings are less susceptible to particle pollution due to effective ventilation, and utility of developed cook-stove types (Yadama et al. 2012).

Figure 1: Share of population without access to modern fuels for developing countries (SADC RENEWABLE ENERGY AND ENERGY EFFICIENCY, 2015)

Three billion people in the world, mostly in developing countries depend on solid fossil fuel including coal, charcoal, wood, manure, and crop residues for household energy requirements. Solid fossil fuel inadequate combustion in primitive unvented stoves produces hazardous emissions including but not limited to carbon dioxide (CO), fine particulate matter (PM2.5, PM10), volatile and semi volatile organic compounds, nitrogen dioxide. According to WHO, coal burning emits heavy metals and sulphur oxide besides the previous emissions. Household air pollution from solid fuel combustion causes more than 3.5 million premature annual deaths and 110 million disability adjusted life years (DALYs) (Clark et al. 2013).

Indoor solid fuel combustion is responsible for premature deaths from obstructive pulmonary disease, lung cancer, and pneumonia (Bonjou et al. 2013). Indoor air pollution because of using solid fuel was classified by WHO as one of the highest hazardous factors of global burden disease (Garelnabbi et al. 2013). Exposure levels in women and children are higher as mothers spend longer hours cooking while carrying their children (Agrawal...
and Yamamoto, 2014). In 2014, WHO indicated that more than 50% of the mortality in children below five years were caused by acute lower respiratory infections (ALRIs) from solid fuel combustion (Ezeh et al. 2014).

In 2012, household air pollution from burning solid fossil fuel was responsible for 4 million premature deaths mainly among the unprivileged population in developing countries. Therefore, new international actions have been initiated recently to boost access to clean household energy resources including the UN initiatives: UN Sustainable Energy for All and the Global Alliance for Clean Stoves programs. Furthermore, the UN has developed new guidelines to minimize exposure to household air pollution from fuel combustion (Bruce et al. 2015) (Fig.2). WHO (2014) declares that there are several intervention strategies to decrease household air pollution and the correlated health outcomes, and classifies the interventions into: interventions related to the pollution source, interventions related to polluted environment, and interventions related to the exposed population behaviour.

Figure 2: Share of the urban and rural populations using solid fuels for cooking in some countries, 2013 (SADC RENEWABLE ENERGY AND ENERGY EFFICIENCY, 2015)

This study aims to investigate the relationship between household air pollution in developing countries and the adverse health impacts on children and adults mainly women, as well as the adverse birth outcomes.

2 Methodology

The paper is based on extensive literature review from recent scholar articles and journals with reference to WHO guidelines and information. In the study, reviewed papers are selected according to the following criteria:

• Papers from peer-reviewed journals.
• Papers published during the period from 2010 to present.
• Papers including data and research conducted in developing countries.
• Papers highlighting the effects of household air pollution mainly on women and children.
3 Literature Review

3.1 Health Risks

Amegah et al (2014) note that around 41% of households in the world mostly in the developing parts of Asia and Sub-Saharan Africa are using solid fuels as the main energy source for cooking. While households in such low to medium-income parts of the world lack proper ventilation, burning the solid fuels in primitive cook-stoves releases hazardous pollutants including carbon monoxide (CO), polycyclic aromatic hydrocarbons PAHs, and particulate matter PM, which caused 4.5 million deaths in 2012 globally.

Reid et al. (2012) indicate that while HAP from solid fuel combustion affects 3 billion people worldwide leading to significant health effects including cancer; women and children are the most vulnerable population. Although HAP from solid fuels including biomass and coal is linked 2 million deaths in 2000, reports from developing countries indicate a growth of population using solid fuel for household energy requirements.

Amegah and Jaakkola (2016) agree that there more than 2.8 billion people world-wide are using solid fuels including biomass and coal for heating and cooking mainly in Asia and sub-Saharan Africa, women and children are the most prone to the emitted air pollutants including PM and CO due to long hours of exposure during cooking. Studies evidenced that acute lower respiratory infections, chronic bronchitis and chronic obstructive pulmonary disease, lung cancer, cardiovascular ailments, stillbirth and LBW, and cataract are allied with susceptibility to HAP. Debbi et al. (2014) also point out that solid fuel combustion in incompetent primitive stoves produces higher levels of household air pollutants including CO and PM compared to WHO suggested levels, which causes 3.5 million deaths annually. Furthermore, household air pollutants from solid fuel combustion cause lung cancer, chronic respiratory infections, cataract, pneumonia in children, and complications in pregnancy outcomes.

Thompson et al. (2014) state that while there are 3 billion people around the world susceptible to HAP from primitive cooking habits, HAP has great impact on neonatal morbidity and death rates. Patelarou and Kelly (2014) report that studies conducted in developing countries evidenced the linkage between HAP and several diseases like cardiovascular ailments, respiratory infections, asthma, chronic obstructive pulmonary disease, cataract, and adverse pregnancy outcomes.

Oluwole et al. (2012) state that household biomass fuel combustion releases air pollutants above twenty times higher than WHO and Environmental Protection Agency suggested limits, which lead to a 1.6 million deaths in 2000 out of which 59% are caused by acute respiratory infections (ARI), and 41% caused by chronic obstructive pulmonary disease (COPD). Moreover, HAP from biomass fuel combustion mainly in rural areas is a major health threat to susceptible women and children; it produces hazardous emissions including PM, CO, volatile organic compounds (VOCs), and carcinogens.

Martin (2012) reports that around 2 million people mostly women and children die annually from exposure to HAP. However, HAP related deaths are now appertaining to three major diseases: lung cancer mostly in women, COPD, and acute pneumonia in children under five years; it has been evidenced that cardiovascular diseases (CVD) are associated with HAP, which will most likely double the annual death rates from HAP. (Fig.3). While HAP is determined to be a preventable source of non-communicable diseases (NCD) including cardiovascular diseases, therefore, mitigating HAP from solid fuel combustion in developing countries may reduce cardiovascular morbidity risks. Moreover, the American
Heart Association specified that particulate matter PM2.5 a major component of HAP is responsible for cardiovascular ailments.

![Figure 3: Impact of cooking with solid fuels on HAP, 2012 (SADC RENEWABLE ENERGY AND ENERGY EFFICIENCY, 2015)](image)

### 3.2 Impact on Adults Mainly Women’s Health

#### Cancer

Oluwole et al. (2012) note that while biomass fuels are mostly used for cooking, therefore women and accompanying children are the most likely to be susceptible to the pollution. It is evident that exposure to household biomass combustion emissions particularly coal emissions is linked with lung cancer, which contributes to almost 1.5% of annual lung cancer deaths. Other health risks linked with biomass fuel emissions in women are cervical cancer, oral cancer, pharyngeal cancer, upper digestive tract cancer, interstitial lung disease, CVD, COPD, cataract, and blindness.

Reid et al. (2012) agree that studies on the correlation between HAP exposure and cancers evidenced that HAP mainly from coal combustion, which is common in China and central Asia; rises the risk of lung cancer. HAP from solid fuel combustion is also linked with upper digestive tract cancer and cervical cancer, however, lung cancer is the most considered in research effort.

Jin et al. (2014) also report that lung cancer is estimated to be the second major reason of cancer mortality in women worldwide. Emissions from household coal combustion are identified as lung carcinogens by the International Agency for Research on Cancer (IARC), while household emissions from biomass; mainly wood; are identified as probably human carcinogens.

#### Cardiovascular Ailments

Lauer et al. (2012) point out that it has been considered recently that the existence of PM2.5 in air is a major risk factor for cardiovascular ailments; therefore, HAP from solid fuel combustion is likely to be correlated with cardiovascular ailments as mentioned in relevant research.
Chockalingam et al. (2012) note that the UN determined that cardiovascular ailments, chronic respiratory diseases, cancer, and diabetes are the main chronic ailments contributing to the global burden of disease. However, research on HAP and cardiovascular ailments is limited, there are evidences that HAP and cardiovascular ailments are correlated, and studies specified that particulate matter in HAP is a significant cause for cardiovascular morbidity and mortality. HAP is also linked to pulmonary hypertension and right heart failure. Garelnabi et al. (2013) note that research in China confirmed that the use of solid fuels for cooking is an important factor to engender HAP. Moreover, burning biomass fuels is hazardous to cardiovascular health because of releasing organic air pollutants, including PAH and PM, which are associated with chronic cardiovascular ailments.

WHO (2016) states that 26% of deaths from HIP are due to ischemic heart disease, moreover almost 35% of deaths (1.4 million deaths) from HAP (HIP) are caused by stroke of which 50% are women due the long period of exposure in the kitchen. Chakraborty et al. (2014) conducted a study in a rural village in eastern India on 50 women, 95% of participants relied on solid biomass fuel for cooking, and the other 5% used liquid petroleum gas (LPG). Results showed that the users of solid biomass fuel experienced changes in systolic and diastolic pressure comparing with women used LPG. Furthermore, Garelnabi et al. (2013) note that a research conducted on Guatemalan women exposed to HAP from solid fuel combustion; confirmed the changes in diastolic blood pressure.

**Lung Ailments**

WHO (2016) declares that women using solid fuel for cooking are more prone to COPD than women using the clean fuel, and specifies that morbidity rates are higher in low and middle-income countries where no access to clean fuel.

Bloomfield et al. (2012) also conclude that the burden of pulmonary hypertension (PH) and right heart failure (RHF) in HAP from solid fuel burning is higher than the burden in chronic lung ailments. Ranabhat et al. (2015) report that in Nepal where 75% of population in villages are depending on biomass fuel for cooking in poor ventilated houses, acute respiratory infections (ARI) has been ranked the first in morbidity every year. A study conducted in the southern rural area determined that respiratory illnesses are main causes of morbidity and death particularly among women and children.

**4 Eye Ailments**

West et al. (2013) argue that while HAP from solid fossil fuel combustion in primitive stoves is correlated with several adverse health effects mainly cancers and respiratory ailments; eye irritation also has been related to HAP. The World Health Organization has stated that 90% of global blind population are living in the developing countries. Furthermore, women are more vulnerable to blindness than men are, as well as to suffer from trachoma and cataract, the most leading eye diseases. While several studies on household solid fuel combustion have reported eye irritation complaints from women exposed to HAP, studies conducted in Guatemala and Pakistan evidenced that women using traditional cook-stoves are more vulnerable to eye irritation than women using developed cook-stoves are. The concurrence of susceptibility to HAP and blindness particularly among women in developing countries forces more research to clarify the casual relationship between both. A literature review study evidenced the correlation between exposure to emissions from household solid fuel combustion and cataract; however, evidences for the correlation with other major eye diseases are insufficient.
4.1 Impact on Pregnancy Outcomes

Patelarou and Kelly (2014) point out that studies evidenced that pregnant women exposed to HAP from solid fuel combustion are more likely to experience adverse birth outcomes than pregnant women using household clean fuels are. Agrawal and Yamamoto (2014) note that studies in India determine that consuming coal and kerosene in households is related to stillbirths, preterm birth, neonatal mortality, and low birth-weight, moreover women using solid fuel and biomass for cooking during pregnancy are at high risk of eclampsia symptoms as observed on women in the age group 15-49 years.

Amegah et al. (2014) report that women in developing countries are mostly exposed to HAP from solid fossil fuels burning, however studies over the past twenty years have linked pregnancy complications to ambient air pollution without enough evidence linking these complications to HAP. As the subject was reviewed, limited studies linked high risk of stillbirth and LBW to HAP from fossil fuels burning. Thompson et al. (2014) conclude after a study conducted in Guatemala on 37 pregnant women from rural areas during prenatal period and later on their infants till the age of 12 months that susceptibility to HAP is higher during prenatal period comparing to neonatal period, however both are higher than WHO instructions. Moreover, susceptibility to HAP results in high rates of neurodevelopmental disorders and LBW.

Oluwole et al. (2012) points out that HAP from biomass fuel is linked with stillbirth, LBW, and prenatal deaths due to high levels of carbon monoxide (CO) in mother’s blood. Pope et al. (2010) clarify that hazardous emissions from household solid fuel combustion like CO and particulate matter PM are responsible for adverse pregnancy outcomes in developing countries including LBW, stillbirth, preterm birth, growth restriction, and other birth defects. While research conducted in Guatemala, Zimbabwe, India, and Pakistan showed that HAP from solid fuel combustion raises the risk of LBW by 38% with a reduction of 96.6gm., other research in India and southern Pakistan reported 51% rise in the risk of stillbirth linked with household air pollution.

Based on a statistical review analysis of 19 studies about the effects of HAP from fossil fuel burning on pregnancy outcomes, Amegah et al. (2014) conclude that a high risk of pregnancy adverse outcomes is associated with household solid fossil fuel burning. The analysis also shows that fossil fuel burning decreases of 86.43gm in the birth weight and results in a 35% rise in LBW risk, as well as high risk of stillbirth, pulmonary Tuberculosis (PTB), intrauterine growth restriction (IUGR), and miscarriage.

4.2 Impact on Child Health

Amegah et al. (2014) state that while HAP from fossil fuel combustion results in lung cancer, and chronic obstructive pulmonary disease COPD in adults, studies proved that it causes acute respiratory infections (ARIs) in children. Lee et al. (2015) identify that acute lower respiratory infections (ALRIs) is linked to HAP results in 39.1 million DALY (disability-adjusted life years) and 455000 deaths every year, furthermore continuous exposure to HAP from burning solid fuels in utero and early childhood affects the immune system in infants and exposes them to acute lower respiratory tract infections. Although data from developing countries are insufficient and limited to animals and in-vitro research, it indicates that burnt fossil fuels emissions especially the particular matter (PM) affect the inborn immunity system and rise vulnerability to infections.

Barnes (2014) states that HAP from solid fuel combustion is linked with Acute Respiratory Infections (ARIs), for instance pneumonia; among children below the age of five years. Children below the age of five years are vulnerable to acute respiratory infections by
household air pollutants due to: lung linings are not totally developed which increases pollutants absorbency, immunity system as well is not totally developed to fight infections, and high breathing rates with narrow respiratory airways and big area of lung surface which allows 50% more of pollutant air than in adults. Moreover, children usually accompany their mothers while cooking during peak hours.

Oluwole et al. (2012) reports that it is also evident that HAP is associated with child deaths, for example child mortality by HAP reaches 19% to 20% in sub–Saharan Africa comparing to 2% to 4% in developed countries (Fig.4). Observational research on children accompanying their mothers during cooking in Kenya, Zimbabwe, Nigeria, Gambia, Guatemala, and India; proved the relation between HAP from biomass and acute respiratory infections (ARIs) in children which causes child mortality under the age of five years. Chockalingam et al. (2012) note that women and children are the most susceptible to HAP from solid fuel combustion, research evidenced high risk of cardiovascular ailments for children exposed to emissions from solid fuel combustion in later years. Thompson et al. (2014) point out that in low-income countries neurodevelopmental disorders are not diagnosed during the neonatal age; therefore, it causes permanent disabilities in later years.

WHO (2014) reports that 50% of mortality in children below five years of age from acute lower respiratory infections (ALRI) are caused by HAP (HAP), and states that children exposed to HAP are at double the risk to suffer from pneumonia.

For example, in Ethiopia, where biomass fuels cover 95% of energy needs, 50,320 children are dying every year from indoor air pollution caused by using the biomass fuel for cooking, therefore, the main reason of mortality among Ethiopian children below five years is the acute respiratory infection (ARI). Studies from Ethiopia has proved that the concentration of PM2.5 in households consuming biomass fuel is toping the WHO guidelines. A cross sectional study on 422 households with children below five years in an urban slum area in Addis Ababa for a period of two weeks concluded that there is a strong relationship between biomass fuel and developing ARI in children under five years old, and that children in households using biomass fuel are three times more expected to suffer. The results of the study are compatible with similar studies in other African countries including Zimbabwe and South Africa (Sanbata et al. 2014).

On the other hand, in Nigeria, 69% of the houses are using solid fuel as the main energy source for cooking. A study was conducted to investigate the impact of using solid fuels on the mortality of children in the age groups 0-28 days (neonatal), 1-11 months (post neonatal), and 12-59 months (child). The analysis of results indicated that the post neonatal and child mortality was related to the use of solid fuels. The study concluded also
that neonatal mortality rate was higher between neonates of mothers consuming solid fuels for cooking (Ezeh et al. 2014).

Furthermore, India is contributing 24% of the annual worldwide child losses as result of ARI, according to the World Health Organization HAP is causing the death of 50% of children with ARI. While in 2010 ARI was responsible for 24% of the total deaths amongst children below five years in India, the latest statistics also suggest that the consumption of traditional biomass fuels in household activities is responsible for 20% of deaths in children below five years. In addition, a research on the subject using a panel data of children from families that are reliant on solid fuels for cooking in six districts confirmed the harmful effects on ARI among children in India (Upadhyay et al. 2015). Another study conducted in southern India targeted four hundred and ninety-seven children from households using fuel-wood concluded that one of the causes of high morbidity among children in Indian slums during the first one thousand days of their lives is the respiratory infections (Kattula et al. 2014).

5 Discussion

All reviewed papers agreed that HAP from solid fuel combustion has adverse health outcomes, and is a major risk factor for morbidity and mortality rates mainly among women and children. Reid et al. (2012), Ochieng et al. (2012), Oluwole et al. (2012), Martin (2012), Amegah, Quansah, and Jaakkola (2014), Debbi et al. (2014), Thompson et al. (2014), Patelayrou and Kelly (2014), and Amegah and Jaakkola (2016) agree that the majority of households in developing countries are using solid fuels including coal and biomass for cooking, heating, and lighting. Moreover, they agree that women and children are the most susceptible to HAP from solid fuels burning in primitive cooking-stoves.

The following studies confirm the correlation between HAP exposure and cancers, particularly in women; including upper digestive tract cancer and cervical cancer, however lung cancer is the most considered in research effort. Oluwole et al. (2012), Reid et al. (2012), and Jin et al. (2014) specify that emissions from coal combustion are linked with lung cancer, which contributes to almost 1.5% of annual global lung cancer deaths. Moreover, Chockalingam et al. (2012), Lauer et al. (2012), Martin (2012), Oluwole et al. (2012), Garelnabi et al. (2013), Chakraborty, Mondal and Datta (2014), Patelayrou and Kelly (2014), and Amegah and Jaakkola (2016) approve the cardiovascular effect of HAP, and identify that (PM2.5) in air pollution is a major risk factor for cardiovascular ailments, however Chockalingam et al. (2012) note that research on HAP and cardiovascular ailments is limited. While WHO (2016) declares that women using solid fuel for cooking are more prone to Chronic obstructive pulmonary disease (COPD) than women using the clean fuel, Amegah and Jaakkola (2016) Martin (2012), Oluwole et al. (2012), Bloomfield et al. (2012), Debbi et al. (2014), Patelayrou and Kelly (2014), and Ranabhat et al. (2015) also agree that household air pollutants from fossil fuel combustion cause chronic respiratory infections, and COPD among women in developing countries. WHO states that 90% of blind population live in the developing countries, West et al. (2013), Debbi et al. (2014), and Amegah and Jaakkola (2016) approve the correlation between HAP, from solid fuel combustion; and eye ailments mainly cataract.

While Patelayrou and Kelly (2014) point out that studies evidenced that pregnant women exposed to HAP from solid fuel combustion are more likely to experience adverse birth outcomes than pregnant women using household clean fuels, Pope et al. (2010), Oluwole et al. (2012), Agrawal and Yamamoto (2014), Debbi et al. (2014), Patelayrou and Kelly (2014), Thompson et al. (2014), and Amegah and Jaakkola (2016) agree to link high risk
of still-birth and LBW to HAP from fossil fuels burning. Moreover, Agrawal and Yamamoto (2014) state that preterm birth and neonatal mortality are linked to HAP exposure, Thompson et al. (2014) note that susceptibility to HAP results in high rates of neurodevelopmental disorder, Oluwole et al. (2012) consider prenatal deaths due to high levels of CO in exposed mother’s blood, Pope et al. (2010) point out that preterm birth, growth restriction, and other birth defects are HAP adverse birth outcomes, and Amegah et al. (2014) mention that HAP exposure is a high risk for pulmonary Tuberculosis (PTB), intrauterine growth restriction (IUGR), and miscarriage.

Chockalingam et al. (2012), Oluwole et al. (2012), Amegah et al. (2014), Barnes (2014), (Ezeh et al. 2014), (Kattula et al. 2014), (Sanbata et al. 2014), Thompson et al. (2014), Lee et al. (2015), and (Upadhyay et al. 2015) state that HAP from solid fuel combustion is linked with ARIs, for instance pneumonia; among children below five years. Similarly, WHO (2014) reports that 50% of mortality in children below five years from ALRIs are caused by HAP exposure. Furthermore, Barnes (2014) explains that children below five years are vulnerable to ALRIs by household air pollutants due to: incomplete development of respiratory system and immunity. Chockalingam et al. (2012) note that research evidenced high risk of CVD for children exposed to HAP in later years. On the other hand, Thompson et al. (2014) point out that in low-income countries neurodevelopmental disorders are not diagnosed during the neonatal age; therefore, it causes permanent disabilities in later years.

6 Recommendations for Future Research

Lee et al. (2015) mention that Animal and in-vitro research based into emissions from biomass combustion examines the effect of certain amounts of PM and does not take into account the real variances in the emitted amounts from different solid fuel types. Therefore, future studies must rely on samples from adults who are naturally exposed to HAP secondary to biomass fuel combustion for more accurate and relevant results.

Thompson et al. (2014) point out that there are no studies published concerning the impact of susceptibility to household pollution on neurodevelopmental disorders in new-borns, thus future research into the subject is essential to mitigate permanent disabilities, low-birth weight, and reduce death rates among children.

Pope et al. (2010) and Patelarou and Kelly (2014) note that the majority of available research on pregnancy outcomes and HAP exposure are qualitative and focus on the effects of ambient air pollution and second-hand smoking. Thus, it is vital to conduct more quantitative studies into linking HAP from solid fuel combustion in developing countries with adverse pregnancy outcomes including LBW and stillbirth, and to obtain precise information about birth weight and stillbirth effects. Additionally, accurate assessment throughout the trimesters to identify the most vulnerable pregnancy phase to pollution.

Patelarou and Kelly (2014) point out that some HAP related studies conducted in developing countries are not in English language. Therefore, it is essential to provide an English version of all HAP related research for easy access to required information. Reid et al. (2012) highlight that most cancerous effect of HAP research efforts focus on lung cancer from coal combustion emissions with insufficient results concerning other types of cancers and other solid fuels. Therefore, there is a need for more targeted research on effects of HAP from different types of solid fuels and cancers other than lung cancer. Further studies on oral and dermal exposure to HAP and cancer are also required, as emissions from solid fuel combustion are likely to contaminate air, surfaces, and food within households.
West et al. (2013) point out that the data about adverse optical outcomes related to exposure to HAP from solid fuel combustion in developing countries is limited to cataract eye disease. Therefore, more studies are required to clarify the subject and to confirm the correlation between HAP exposure and major eye diseases causing high rates of blindness other than cataract in developing countries.

7 Conclusions

According to WHO, HAP from solid fuel combustion is the main global health threat today causing 4.3 million premature deaths worldwide annually. Evidence of adverse health outcomes from HAP is strong, as a significant number of health outcomes are proved to be correlated with exposure to HAP. Exposure is recorded to be higher in women and children under five years.

HAP from solid fuels is mostly linked to poverty and is considered a risk factor for health outcomes with major impact on children including ALRIs, still-birth, and LBW; as well as several adult major non-communicable diseases including CVD, COPD, and lung cancer. Many studies conducted on exposed households determine that susceptibility levels mainly to PM2.5 exceeds WHO air quality guidelines (AQG), and that pregnant women and children below the age of five years are furthermore affected. Therefore, significant interventions to reduce HAP exposure can decrease adverse birth outcomes and child mortality in developing countries. Advanced cook-stoves and clean fuels are two challenging interventions to reduce HAP in low-income settings due to socio-economic restrictions. It has been evidenced from variable studies that HAP rises the risk of child morbidity and mortality, therefore introducing interventions that reduce HAP with PM2.5 close to WHO air quality guidelines is expected to minimise the risk of the three major child health outcomes, ALRIs, still-birth, and LBW; by 29% - 39%.

More than 4.3 million people are dying annually from diseases related to HAP from solid fuel combustion mainly for cooking. Therefore, it is essential to provide global access to alternative clean resources of energy to avoid millions of deaths and develop the health of billions of people. There is a majority of low-income households in rural areas that count on free biomass fuel, which makes it challenging to implement intervention strategies comparing with rural areas where the population is paying for the solid fuel. Therefore, successful intervention strategies must consider the socio-economic status of the targeted population.

References


PERFORMANCE GAP? ENERGY, HEALTH AND COMFORT NEEDS IN BUILDINGS

Arman Hashemi¹, Minna Sunikka-Blank², Eugene Mohareb³, Tatiana Vakhitova⁴, Dimitra Dantsiou², Hui Ben² & Tania Sharmin²

¹ School of Environment and Technology, University of Brighton, UK, a.hashemi@brighton.ac.uk
² Department of Architecture, University of Cambridge, UK, mms45@cam.ac.uk
³ School of the Built Environment, University of Reading, UK, e.mohareb@reading.ac.uk
⁴ Granta Design Ltd., Cambridge, UK, tatiana.vakhitova@grantadesign.com

Abstract: Research on performance gap suggests that the actual energy consumption in buildings can be twice as much as expected. Energy models rely on predictive indicators and assumptions that are usually done at design stage, without acknowledging behavioural patterns of actual users. Moreover, in the context of performance gap, it is evident that energy efficiency is overemphasised while other key issues such as health and comfort of occupants, indoor air quality, noise levels etc. have been less stressed and discussed. This paper discusses the performance gap using surveys and physical measurements in a case study building at the University of Cambridge and reports findings of a research workshop with graduate students working on environmental performances of the built environment. The workshop addressed research issues related to energy, comfort and health, used as a method to understand the complexities of and trade-off between different aspects of sustainable buildings. According to the results, it is possible to balance energy, health and comfort needs in building projects. Lessons can be learned from the university’s old and new building projects to inform future research and policies.

Keywords: Performance Gap, Energy, Health, Thermal Comfort
1 Introduction
Buildings contributed to a substantial share of total UK energy demand in 2015, with domestic and non-domestic buildings making up 43% of the all energy consumption (Department of Energy & Climate Change 2016). Additionally, they accounted for 18% of the UK's greenhouse gas (GHG) emissions in 2015, with 75% of this share attributable to residences, 15% to commercial buildings and 10% to public sector buildings (Committee on Climate Change 2016). In particular, space heating was the largest energy end use, estimated to contribute up to 60% of total demand in households (2011) and 45% in commercial buildings (2009) (Palmer et al. 2013; DECC 2012). The successful long-term reduction of energy demand and related GHG emissions will require that high-performance buildings replace the existing energy-intensive building stock (Mohareb & Kennedy 2014). However, many modern high-performance building projects have produced an actual level of energy performance that does not match up with projections modelled during their design. This has come to be referred to as the "performance gap", which is a product of a number of technical and behavioural, described below.

The misalignment with design estimates and actual energy demand have been uncovered through an increase in use of post-occupancy evaluation, largely motivated by the surge in interest in certification of high-performance buildings. An early application of post-occupancy evaluations was in the UK PROBE study, which found energy performance was generally higher than anticipated (Bordass et al. 2001). The performance gap has appeared in various building end-use types and with a range of severity. A recent review stated found post-occupancy energy demand exceeded modelled values by 34% with a standard deviation of 55% for 64 non-domestic projects studied (van Dronkelaar et al. 2016). One case study office building assessed by the Carbon Trust (2011) demonstrated a nearly five-fold increase in energy demand relative to the energy performance certificate estimate. Even in Carbon Trust case studies where more detailed modelling was completed, there was a 16% increase in actual demand relative to modelled results. While performance occasionally improves upon predicted values, the Carbon Trust (2011) estimates that 75% of the variances are buildings where energy demand was higher than design specifications.

High-performance domestic buildings face similar issues in matching design specifications of energy demand. The Energy Saving Trust (2008) found that insulation measures in over 1500 UK domestic homes studied achieved a energy demand that was 50% less than what was expected, on average. Calì et al. (2016) examined a sample of recently-refurbished German multi-unit residential buildings and performance gap of up to 95% in the first year after retrofitting for one building. Further, Johnston et al. (2016) state the studies of new-build dwellings in the UK have demonstrated actual energy performance that were more than double predicted values.

This performance gap is not unique to the UK; a US analysis of LEED-certified buildings found an equal number of buildings performed worse than estimated versus those that performed better - indeed, some of these high performance buildings had greater energy demands than the energy code baseline (Turner & Frankel 2008). Similar underperformance has also been observed in New York City office buildings, with LEED-accredited office buildings often having higher energy use intensities than conventional office buildings (Scofield 2013).

A performance gap fundamentally implies higher energy consumption (and associated costs) than the occupant will have anticipated. In one case studied by the Carbon Trust
an additional £10/m² in unanticipated annual operating energy costs was observed by occupants in a particularly poor performing building. In pay-as-you-save energy retrofit schemes, the underperformance can be a burden on either the energy performance contractor or the building owner or occupant; where the realised savings do not match those that had been budgeted for, longer payback periods can result, as well as added costs and the potential for contractual disputes (van Dronkelaar et al. 2016).

A number of technical deficiencies with respect to materials and installation can lead to diminished energy performance relative to modelled projections. These include:

a) Calculations or simplifications in modelling software are inconsistent or not checked/revised throughout the delivery process (Sunikka-Blank & Galvin 2012; Carbon Trust 2011; De Wilde 2014; Schwartz & Raslan 2013).

b) Higher efficiency materials and equipment can provide lower than expected performance (Baker 2008; Rye & Scott 2012; De Wilde 2014).

c) Materials themselves may not be correctly installed per design specifications due to poor workmanship or inexperienced installers (Sunikka-Blank & Galvin 2012; Carbon Trust 2011; De Wilde 2014; van Dronkelaar et al. 2016).

d) Buildings may not have been commissioned properly upon completion (Carbon Trust 2011; De Wilde 2014).

Unregulated loads were not properly considered in the modelling process (Carbon Trust 2011).

f) Building designs themselves may be inherently flawed or design characteristics/goals poorly communicated (De Wilde 2014).

g) Poor communication between landlord (involved during the design process) and future occupants with respect to optimal building operation (Robinson et al. 2016)

h) Split incentive to fulfil energy performance between the building owner and tenant (Robinson et al. 2016)

i) Occupant behaviour is markedly different from design estimates (De Wilde 2014; Menezes et al. 2012; Haldi & Robinson 2008; Calì et al. 2016).

The complexity involved in building construction and occupant behaviour leads to a number of solutions that should be considered in effectively addressing the performance gap. In one German case study, Calì et al. (2016) found that through careful post-occupancy monitoring was able to remedy building performance issues related to technical issues with heat pumps and wide variation in occupant behaviour. As well, Johnston et al. (2016) were able to match expected energy demand through the careful quality control systems inherent in the PassivHaus certification process applied in their cases.

With respect to non-domestic buildings, Fedoruk et al. (2015) suggest that, in the case of a showcase high performance building on the University of British Columbia campus (Centre for Interactive Research on Sustainability), the performance gap was mostly attributable to issues outside of shortcomings in installed building components. They go on to state that it could have been reduced through building energy monitoring, improved integration between designers and builders (such as through design charrettes; Mollaoglu-Korkmaz et al. 2013), and expanding current boundaries of energy analysis beyond the building itself. Robinson et al. (2016) suggest a mandatory post-construction review (per BREEAM for New Construction's 2014 guidelines) and the 'soft landings' approach of continual post-occupancy communication between designers, owners, and occupants (directed by the CIBSE TM54) can contribute to a better match between anticipated and actual demand. From a legislative perspective, a regulatory framework to govern energy underperformance in buildings (van Dronkelaar et al. 2016). The authors also note the need for better monitoring for data collection, as well as more training that targets energy-
related technical and communication skills in the building sector (construction and operation). Finally, Tuohy & Murphy (2014) suggest that through reshaping the aims of BIM to include actual building performance, providing ratings/awards based on actual performance, and the adoption of a more robust feedback systems in the design process, greater accountability can be realised with respect to actual energy demand.

It is evident from the above that the importance of energy consumption in buildings is well represented in the literature, while other important issues such as health and wellbeing of occupants, indoor air quality, thermal comfort, noise levels etc. require further study. It is in this context that this paper sets out to investigate performance gap to collectively address the abovementioned issues in buildings. To this end, a workshop was organised to study energy, health and comfort needs in a case study building at the University of Cambridge. The workshop was a continuation of EU Marie Curie FP7 project ‘Uni-metrics’ on sustainable campuses. The workshop mainly aimed to a) develop a common understanding of research problems in energy efficiency, comfort and health in buildings; b) identify knowledge gaps; and c) gain understanding from research projects that have addressed performance gap, comfort and health in buildings.

2 Energy use in University of Cambridge

The University of Cambridge has a total floor area of 642,000m², over 330 buildings and 150 departments and institutions. The capital building programme is £60M/pa (plus £15M for equipment). There are 18,900 students and 9,800 staff studying and working at the university. In 2013-2014 the University spent £16 million on energy. The University spends £1,825 every hour (or around £30 every minute) on energy. Figure 1 shows the top 30 users of electricity in the campus (Environment and Energy Office 2016).

![Figure 5: Top 30 users of electricity, ranked by usage per kWh/m² (Environment and Energy Office 2016)](image)

The actual energy consumption can be twice as much as expected. The University of Cambridge has also observed performance gap issues; for example, regulated electricity and gas consumptions for Sainsbury Lab at the university are around 130% and 284% of the design estimates, respectively. Solar photovoltaic (PV) panels have provided energy as predicted, but only equivalent to 50% of the 10% reduction required by the Merton Rule. High occupancy rates outside core office hours have been reported as a major issue affecting energy performance. Thermal comfort is also an issue, as accounts of high...
temperatures have been noted in some offices. More individual controls over the environment has been suggested as a solution to improve thermal comfort (Lee 2014; Khatami et al. 2014). According to the university’s policies on thermal comfort, air conditioning should only be allowed for specific academic needs assuming that “occupants will moderate their own comfort by dressing appropriately for their preference” (University of Cambridge 2016).

3 The Case Study

The selected case study was the Faculty of History in Cambridge (Figure 2). The design of James Stirling was selected based on an architectural competition in 1962. From the beginning, there were concerns about the building’s environmental performance ‘the building would be subject to solar heat to a fairly large extent’ (EMBS files 1963). The building was funded by the Universities Grants Committee (UGC), which meant that the funds had to be spent within a certain time frame and there was pressure to reduce the number of design iterations. The project was well funded; the contract price was £104/m² which amounts to £2440/m² at current prices. The design accommodates the history faculty, with an L-shaped stacked block of 6 levels enclosing a large fan-shaped glazed central space that houses the library. Early in construction, a poor relationship was reported amongst all parties, along with time / cost overruns and leaks were noted during the handover of the building. Due to neighbours’ complaints an adjustment and reorientation of the building was made. After two decades of contending with construction and thermal comfort issues, demolition was considered in 1985 but the building was conserved and “grade II” listed in 2000 (Figure 2).

Figure 6: Faculty of History

Main reason for poor thermal comfort and high energy use is that 75% of the envelope above the plinth is standard industrial glazing, along with the giant stepped-pyramid skylight of the library (Figure 3). The glazed, double-skin roof in the library was meant to acts as a light diffusing layer where the inner layer was obscured to prevent glare and to give shadowless light in the reading area. This was also designed to insulate the cavity between the two skins so that all the louvres in the vertical steps would be closed in winter and opened in the summer to enable ventilation through the stack effect. Artificial light sources in the cavity and the roof provide an ‘overhead spectacle’; however, the library space and office spaces are prone to overheating in summer (and draught in
winter). The noisy extract fans in the library were never used and small air-conditioning units have been placed in the administrative corridors. Offices have draughty glass louvres for ventilation, along with secondary glazing and venetian blinds that have been installed in later renovations. It was predicted as early as 1968 that “controls will be fouled up through mismanagement by the humanities-oriented occupants who are below the average in mechanical literacy and competence, while the occupants will take verbal revenge on the architects - whereas revenge should be on UGC and their budgets that are too ‘skimpy’ to permit decent environmental installations or idiot-proof control systems” (Banham 1968).

![Glazed, double-skin roof of the library](image)

The building got mixed reviews from the beginning. Brogan (1968) accused Stirling of ‘complete disdain’ for the users of their buildings and being ‘not so much undemocratic as anti-democratic: structural fascists”. On the other hand, Banham who is an acknowledged architectural critique in Britain commented in Architectural Review (1968) that ‘the result, respectful to Cambridge at a more fundamental level of what Cambridge actually does, presents a startling critique of buildings that have tried to be respectful to Cambridge at the superficial level…the sad things is that Cambridge opinion will eventually accept it as part of the ‘Cambridge traditions’ and then no one will have the guts to pull it down when the useful life for which it was designed has come to an end”.

### 4 Physical Measurement

Physical measurements were carried out during February-August to evaluate indoor conditions and thermal comfort as well as the energy consumption in the case study building. Data loggers were installed on five different floors of the building to assess the conditions in various areas including in the main library, as well as corridors and office buildings. Table 1 shows the annual electricity consumptions of the case study building between 2005 and 2014. According to the results, the annual energy consumption over the period between 2005-2014 has remained nearly constant, averaging 216,549 kWh per annum, or 49.3 kWh/m² (for a total floor area of 4393m²).

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
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<td>87</td>
<td>08</td>
<td>60</td>
<td>48</td>
<td>26</td>
<td>91</td>
<td>46</td>
<td>68</td>
<td>78</td>
</tr>
</tbody>
</table>

Figure 4 and Figure 5 show the internal temperatures and relative humanity as well as the external temperatures during one year in different areas of the building. According to the
results, the building has been thermally uncomfortable in almost all areas. The internal temperature in many areas has reached 35 °C; the indoor temperature in the rooms/offices between July and August has frequently been over 30 °C. The temperature in the main library on the ground floor has also fluctuated greatly and in many cases has exceeded 30 °C. Meanwhile, CIBSE Guide A 2015 recommends average summer operative temperatures of 24-25 °C for libraries and 22-25 °C offices, respectively (CIBSE 2015).

The situation has been considerably worse in the corridors on the 6th floor (Figure 6) as the temperature has reached nearly 50 °C which is an indicator of severe, and potentially dangerous, thermal comfort conditions for the occupants. Extremely high indoor temperatures in the building necessitated the use of air conditioning units particularly on the higher floors. According to Figure 5, occupants also experience extremely low temperatures (between 10 °C and 15 °C) during winter. Such conditions indicate high heating and cooling requirements in the case study building during both winter and summer. Yet, considering benchmarks, the average electricity consumption of 49.5 kWh/m² is rather low. A possible explanation for this may be the seasonal use of the building by the occupants.
5 The workshop
The participants (Figure 7) were provided with the above information on the current performance of building including the physical measurements. The participants also visited the case study building and spoke with occupants and facilities managers to identify and evaluate the current conditions, as well as the problems of the building.

Three themes were identified as the core subjects which needed to be investigated while developing solutions:

A. Energy: e.g., lighting, equipment, building envelope, renewable energy etc.
B. Architecture: e.g., interior/exterior, extension, partitions, retrofit, demolition
C. Comfort and Health: e.g., thermal comfort, indoor air quality, noise, glare, ventilation.

5.1 Summary of proposals and findings
Group A followed an approach divided in three sections: a) identification of problems; b) proposed energy efficiency measures; c) cost/time/benefit assessment of proposed measures. After the walkthrough inside the case study building (History Faculty), the group discussed the elements that could lead into inefficient energy use. The following issues were raised:

- Building users unable to understand and operate the building’s passive features (glass louvre ventilators, venetian blinds).
- Air conditioners placed in corridors as an additional way of heating/cooling indicating the inefficiency of the existing heating/cooling system.
• Lights left on in corridors and library while the building was almost unoccupied.
• Window blinds that were meant to prevent overheating to obstruct daylight.
• Extract fans of the existing mechanical ventilation system deactivated due to noise.

In terms of the proposed efficiency measures, the group emphasised the need to respect the building's aesthetic quality through discrete material interventions while focusing on educating the users on the proper use of its passive features and systems. The following efficiency measures were proposed as solutions to improve the energy performance of the building:

a) Fritted glass for the outer layer of the double-glass envelope that assists with the building’s natural ventilation scheme, daylighting and weather shielding. The pattern of the fritted glass will be specially designed for the building to enhance its aesthetic value and diffuse light as it enters the building, reducing glare as well as solar gain.

b) Behavioural nudging from an interactive ‘building wizard’ accessible through the building’s Wi-Fi.

c) Building user guide to be provided during staff inductions and along with guidance on the proper use of the building’s passive and active systems and controls.

d) HVAC with heat recovery system to replace the existing noisy ventilation system.

e) PV panels in southern-facing façade to provide electricity for light-emitting diode (LED) lighting.

f) Reprogramming of movement lighting sensors in shorter time intervals.

g) Carpeting the library for noise reduction.

h) Thermal buffer zone in the entrance to prevent heat loss.

The practical aspects related to the implementation of the proposed interventions (cost, benefit, timeframe) were presented in a comparative graph. The different measures were plotted based on their cost (high, medium, low), the timeframe of their implementation and their impact on energy efficiency and comfort (small, medium, high) (Figure 9).
In terms of comfort and energy efficiency, the replacement of the outer layer of the building’s glass envelope with fritted glass and the behavioural nudges were the interventions with a higher expected impact. The new façade intends to give a creative and delicate aesthetic touch, enhancing the identity and popularity of the building however, this is anticipated to be a costly intervention. The interactive ‘building wizard’ would be less costly but needs constant update and monitoring. The case where the two measures are combined is seen as the optimal intervention in the existing context.

**Group B** explored three discrete options for a fundamental shift in the building’s operation. These options focused on changes in end use, energy demand/supply systems, and building services systems. The discretisation of these options was understood to be purely theoretical, as components of the three options would likely be considered in any planned building upgrade. However, for the sake of the workshop exercise, it was pursued in the interest of a deeper understanding of the value of each approach.

The options were assessed using four main criteria, which included six sub criteria: cost (capital and operating), time required for implementation, user impacts (during transformation and post transformation), and aesthetic impacts (heritage and public perception). While the intention of most of these criteria are self-evident, the aesthetic impacts require further explanation. The “heritage” component relates to the preservation of the original architectural value of the building, especially in conforming with its Grade II listed building status. The “public perception” aesthetic feature was based on the assumption that the general public does not view the current modernist design favourably and would welcome an upgrading of the exterior of the building. A summary of the evaluation of the three options is provided in Table 2.

<table>
<thead>
<tr>
<th>Proposed Change</th>
<th>Cost</th>
<th>User Impact</th>
<th>Aesthetic</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capital Cost</td>
<td>Operating Cost</td>
<td>Mid-Transform.</td>
<td>Post-Transform.</td>
</tr>
<tr>
<td>User</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Energy Demand/Supply</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Building Services</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

The first option for transforming the building assessed the problems surrounding the building’s primary end uses as a library and for faculty office space. Given the problems with overheating in the summer and difficulties maintaining a sufficiently warm temperature in the winter, the conversion of the building to a more compatible end-use, such as botanical research lab, seemed worthy of consideration. The ample solar access and the inhospitableness for humans lead to this suggestion. This would also be a relatively low cost solution, requiring an exchange of users from the poorly conditioned Sainsbury Lab for botanical studies, for example. The time requirement would likely be low, and the heritage value could be retained. Mid-transformation impacts and public perceptions scored low, but it was projected that user satisfaction would be very high after the relocation.
The second option involved a substantial investment in low-carbon technologies for the building. While the library's skylight structure would be retained, it would be covered with PV panels. The natural lighting would be reduced substantially and the interior of the glazing would be fitted with special LED panels that could be used to project images of the sky or any other suitable visuals that would be pleasing to the library occupants. The PV panels would supply electricity to meet demand within the building, with any excess production being converted to heat for a borehole thermal energy storage network located on the Sedgwick site. The building envelope would also be upgraded to meet high performance standards and reduce heating/cooling demand.

This approach was deemed to require high up-front investment, be disruptive to occupants during the construction phase, take the greatest time to complete and negatively affect the heritage value of the building. The participants agreed that loss of the heritage aesthetic would be an increasingly unavoidable issue in meeting the necessary improvements of building stock performance towards the University’s 2050 GHG reduction goals. The energy supply and demand improvements were expected to perform well in post-construction operating costs and user satisfaction, as well as public perception of its updated facade.

The final option that was assessed was the improved building services approach which focused on automation and highly-sensitive occupant detection systems. This option envisioned automated building service controls, coupled with redesigned heating and ventilation systems that serviced zones on the scale of individual offices. These zones would be equipped with motion, CO$_2$, and humidity sensors, with highly-structured user feedback systems, enabling fine-tuning of controls of the building services. This approach was projected to be costly in both construction and operation, with the latter requiring frequent servicing of the advanced control systems and heating/ventilation network. As well, while the installation of such a scheme might be less invasive to users during its installation, it was expected to require more work in keeping the user feedback system ‘tuned’ and take a long time to install. The heritage value of the building would be retained, but this approach would not improve public perception as no externally-visible upgrades would be included.

Ultimately the group felt that a focus on changing the end user would score the best if all criteria were weighted equally. However, the weighting of the criteria would depend on the goals and constraints. As well, each option had merits and a more integrated implementation of these could remedy the detriments of each of the others.

6 Conclusions
This paper discussed the performance gap using surveys and physical measurements in a case study building at the University of Cambridge. Overheating was identified as the major issue contributing to thermal discomfort and high energy consumptions in the case study building. Various design, operation and management solutions, such as lighting and ventilations strategies, user controls, renewable energy as well as options such as complete change of use etc., were suggested by the workshop participants to improve the conditions in the building.

According to the results of the paper, there is a need to challenge narrowly focused perceptions of energy efficiency. When it comes to performance gap, health and comfort should be considered alongside the energy efficiency. Indeed, health and wellbeing of occupants should be the main driver rather than energy efficiency in building. Substantial savings could be achieved by fixing the technical problems, disaggregating consumption
data and encouraging behavioural changes of end-users. Moreover, there exists a need to understand actual occupancy patterns, user requirements and social norms in the workplace in order to effectively address and improve both energy performance and comfort in buildings. In this respect, although technical deficiencies and information gaps play an important role, all stakeholders including clients, designers, builders, policy- and decision-makers need to understand potential trade-offs between aesthetic, comfort and energy values to close the gap.

Acknowledgements
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PHASE CHANGE MATERIALS (PCMs) INTEGRATED INTO CONCRETE BLOCKS TO REDUCE COOLING LOAD IN HOT CLIMATE

Ahmed Hassan¹, Khaled A. Al Sallal², Hamza Alnoman³, Yasir Rashid⁴ & Shaimaa Abdelbaqi⁵

¹,²,³,⁴,⁵ College of Engineering, United Arab Emirates University, UAE.
¹ ahmed.hassan@uaeu.ac.ae, ² k.sallal@uaeu.ac.ae, ³ ha1987@uaeu.ac.ae, ⁴ yasir.rashid@uaeu.ac.ae, ⁵ 200734406@uaeu.ac.ae

Abstract: Phase change materials (PCMs) contained in an insulated concrete block are tested in extremely hot weather of UAE to evaluate its cooling performance. An insulated chamber is constructed behind the block containing PCM to mimic a scaled down indoor space. The effect of placement of the PCM layer on heat gain indoors is studied at two locations, i.e., adjacent to the outer as well as the inner concrete layer. Inclusion of PCM reduced heat gain through concrete blocks compared to blocks without PCM yielding a drop in cooling load indoors. The placement of PCM and insulation layers adjacent to indoors exhibited better cooling performance compared to that adjacent to the outdoors. In the best case, a temperature drop of 8.5 % and a time lag of 2.6 h is achieved in peak indoor temperature rendering a reduction of 44 % in the heat gain. The research recommends to select a PCM with melting point higher than average summer night time temperatures placed adjacent to interior construction layers.

Keywords: Phase change material; Thermal management; Building insulations; Concrete blocks, Cooling load.
1 Introduction

Conventionally, phase change materials (PCMs) have been applied to building skin mainly as a cavity filled layer with various integration schemes (Mathieu-Potvin 2009, Diaconu 2010, Huang 2006, Lee 2015, Jin 2014, Selka 2015) as outlined in Fig. 1 (A-E). The previous studies conducted in both winter seasons (Mathieu-Potvin 2009, Diaconu 2010, Huang 2006) and summer seasons (Lee 2015, Jin 2014, Selka 2015) proved the effectiveness of the PCM in reducing heating as well as cooling load. The most effective PCM integration design in wall sections was reported by (Lee 2015) shown in Fig. 1-D that achieved a drop and delay in the peak heat flux by 51 % and 6.3 h respectively (Lee 2015). Apart from PCM integration into conventional building materials, PCM have been contained beneath building-integrated photovoltaic system showing a drop of up to 30 % in heating and 55 % in cooling load (Koşny 2012). Although, the PCMs are effective in reducing energy demand in buildings, right selection of their phase change temperature needs to be investigated for different climatic conditions. Additionally, the placement of the PCM layer with respect to outdoors/indoors (Heim 2016, Evola 2014) is also least studied in various climates. The limited previous research on PCM melting point selection contradicts suggesting a higher (Neeper 2000) as well as a lower (Heim 2004) temperature than the desired indoor temperature to achieve indoor comfort. More recent studies, however, have overcome the contradiction by linking PCM melting point to night time ambient temperatures in order to regenerate the PCM passively in hot climates (Hasan 2016).

![Figure 1: Previously investigated configurations of integrating phase change materials (PCMs) in walls.](image-url)
The current study attempts to validate the selection of PCM melting point linked to outdoor ambient temperature along with the optimal placement PCM in a wall section in UAE. A paraffin based PCM (Rubitherm 2016) with a melting point higher than average summer night temperature in Al Ain, UAE is selected for this study. The research investigates the cooling effect produced by integration of PCM into a concrete block in two arrangements. The cooling effect is quantified by drop in the temperature at front surfaces of wall sections and the indoor air.

2 Materials and Methods

Three concrete blocks, one without PCM (block A) and the other two containing PCM (block B and block C) are employed in the experiment. A scaled down test chamber with dimensions of 40 cm x 40 cm x 40 cm is constructed from polystyrene insulations to mimic an indoor space behind the blocks. A paraffin based commercial PCM: RT42 is filled in an air cavity within two concrete layers guarded by polymer layer for leakage control. Multiple t-type copper–constantan thermocouples calibrated in ice-bath with a measurement error of ±0.3 °C are employed to measure temperature. A self-powered Apogee pyranometer (Apogee Instruments 2016) is installed to measure global solar radiation intensity (G). All the sensors are connected to an NI compact Rio (NI cRIO-9073) data acquisition system (National Instruments 2016). A weather station (Starmeter-WS1041) is employed to measure ambient temperature ($T_{amb}$) and wind speed ($v_w$). The temperatures are measured at the front surfaces of ($T_{af}$), ($T_{βf}$) and ($T_{ωf}$), and inside the test chamber ($T_{αi}$), ($T_{βi}$) and ($T_{ωi}$) block A, B and C respectively as shown in Fig. 2.

Figure 2: Schematic diagram of the experimental set-up showing configuration of the block C (the same set-up is used for the block A and the block B).

3 Results

Fig. 3-A depicts that for the sample day, the G remained fairly stable being 230 W/m² at 7:00 and increasing afterwards with a stable gradient reaching the peak value of 944 W/m²
at 12:10. Total solar energy received by the concrete surface is calculated employing equation 1.

\[ Q_{in} = \sum_{i=1}^{n} G_i \times A \times \varphi \times t_i \]

Where \( Q_{in} \) is the solar energy absorbed by concrete blocks (Wh/day), \( G \) is the global solar radiation intensity incident on the surface (W/m\(^2\)), \( A \) is the surface area of the concrete block facing south (40*40 cm\(^2\)), \( \varphi \) is the absorptance of the concrete (0.65) and \( t \) is the time in hours. The \( Q_{in} \) ranged from 679 Wh/day to 740 Wh/day between the tested days with a mean value of 709 Wh/day.

The \( v_w \) remained generally higher during daytime and dropped to 0 m/s at night time exhibiting a smooth profile when averaged for 14 days as shown in Fig. 3-B. Equation 2 and 3 are used to calculate heat transfer coefficient (hc) by applying linear and power regression (Sharples 1998). The hc remained on average at 9.6 W/m\(^2\).K and 14.1 W/m\(^2\).K for night time and daytime governing heat losses and self-cooling mechanism.

\[ h_c = 3.3 \times v_w + 6.5 \]

\[ h_c = 9.5 \times v_w^{0.48} \]

Figure 3: Global solar radiation intensity (G) and wind speed (\( v_w \)) for A) the sample day and B) average of the 14 days.

Effect of inclusion of the PCM in the concrete blocks can be observed by comparing temperatures at the front surface of the three blocks, A (\( T_{af} \)), B (\( T_{bf} \)) and C (\( T_{cf} \)) shown in Fig. 4 A and 4 B. Temperature drop yielded by the block B and the block C (\( T_{bf} \) and \( T_{cf} \)) compared to the reference block A (\( T_{af} \)) is presented in the inset windows of Fig. 4-A and 4-B. The temperature drop is negligible at the start of the experiment, however, it increased gradually reaching the peak value of 2.3 °C and 4.1 °C for blocks B and C respectively at 15:10. The block C achieved higher cooling during daytime compared to the block B mainly due to placement location of the PCM. In case of the block C, the PCM layer is placed closer to the outer concrete layer while in case of the block B, the PCM is placed closer to the inner concrete layer. Both the arrangements have an air cavity in proximity for natural ventilation. It highlights that placement of the PCM layer can be an important consideration while integrating PCM into building depending on whether heat needs to be retained (cold climate) or removed (hot climate) (Lee 2015, Hasan 2016). The negative temperature drop
at night shows slower self-cooling of the blocks B and C (due to higher heat retention) compared to the block A. Heat absorbed in the PCM can be circulated into indoors of the building in colder climate (or winter season) to reduce heating load (Zhou 2015). In the hot climate, the challenge posed is to discard the heat absorbed by the PCM to regenerate the PCM to solid and avoid overheating in the building (Hasan 2015).

The reduced surface temperatures resulted in a drop back surface as well as indoor temperature (Fig. 5-A and 5-B) in the test chambers B \( (T_B) \) and C \( (T_C) \) compared to the test chamber A \( (T_A) \) as shown in with the drop in temperature in the window graph. The difference was negative at start of the experiment and became positive at 08:50 for both configurations. The chamber B yielded generally a lower temperature drop with a maximum value of 1.4 °C, nevertheless, it stayed positive for most of the day and night. The chamber C rendered a higher temperature drop with the peak value of 3.1 °C, however, it stayed positive mainly during daytime up to 12 h. The configuration of the chambers B and C produced 5.4 % and 8.5 % higher cooling effect indoors respectively on average compared to the reference chamber A during daytime.
The reduced indoor temperatures reflect a drop in heat transfer indoors calculated by equation 4.

\[ Q = h_c \times A \times (T_b - T_i) \]  

Where Q is heat transfer rate, \( h_c \) is convective heat transfer coefficient, \( T_b \) is the back surface temperature, and \( T_i \) is the indoor air temperature. The \( h_c \) value at the back surface facing indoors is found to be 6.5 W/m\(^2\).K calculated by assuming free cooling employing zero air velocity in equation 2. Cooling load saving is calculated by the difference of heat transfer rates between the back surface and the indoors for the reference (A) and the blocks containing the PCM (B and C). Fig. 6 shows that the block B (with the PCM layer closer to the interior) achieves a higher reduction in heat transfer compared to the block C with the PCM closer to the outer layer. The reduction in the heat transfer on 24 h balance was 137 Wh/m\(^2\) and 32 Wh/m\(^2\) for the block B and the block C respectively. The heat gain reduction was 44% by the block B and 10.5% by the block C on 24 h basis compared to the block A. It is observed that the optimal PCM melting point occurs at few degrees higher than the night time summer temperatures. Also, the PCM should be placed towards interior construction layer for optimal performance in hot climates.
Figure 6: Average cooling load reduction achieved by the block B and the block C compared to the reference block A for 24 h and for daytime only.

4 Conclusion

A paraffin based PCM is integrated into concrete blocks in two different arrangements and tested in hot climate of UAE in extreme month. The cooling produced by the PCM in both configurations is determined. Inclusion of the PCM reduced heat transmission to indoors by 44 % (block B) and 10.5 % (block C) at 24 h energy balance. Additionally, a time delay of 2.6 h is observed in the peak indoor temperature at the maximum. The block B remained cooler compared to the reference block A during daytime and most of the night time. The block C remained cooler than the reference block A during daytime and warmer during night time. Both the PCM inclusion arrangements, however, prevented 137 Wh/m² and 32 Wh/m² heat transmission based on 24 h energy balance for the block B and the block C respectively. It is concluded that the PCM melting point should be kept higher than the average summer night temperature of the site of PCM deployment. The research suggests that the optimal PCM melting point occurs at few degrees higher than the night time summer temperatures. Also, the PCM should be placed towards interior construction layer for optimal performance in hot climates. The research concludes by identifying an optimal PCM melting point as well as placement for extremely hot climates.

Nomenclature

\( A \)  
Surface area of the concrete block (m²)

\( CV \)  
Coefficient of variation (%)

\( G \)  
Global solar radiation intensity incident on the surface (W/m²)

\( hc \)  
Convective heat transfer coefficient (W/m².K)

\( HVAC \)  
Heating, ventilation & air conditioning

\( m \)  
Mass of the concrete block (kg)

\( PCM \)  
Phase change material

\( Q \)  
Heat transfer rate (W/m²)

\( Q_{\text{in}} \)  
Incident solar energy (Wh/m²)

\( Q_{\text{sav}} \)  
Energy savings (Wh/m²)

\( SD \)  
Population standard deviation

\( T \)  
Temperature (°C)

\( t \)  
time (h)

\( v_w \)  
Wind speed (m/s)

Subscripts

\( \alpha \)  
Reference block A

\( \beta \)  
Block B
γ Block C
f Front surface
i Indoor air

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5 References


HASAN, AL-SALLAL, ALNOMAN, RASHID, & ABDELBAQI_A53 277


Abstract: Consumers have long since marveled why air conditions (HVACs) are not providing the temperature determined in their thermostat’s set point. The air temperature measured is integrated in the device. If buildings are not properly insulated, however, the ambient temperature tends to follow the ups and downs of the outside temperature, and not the request of the installed thermostat. As a remedy, this article tests an unassuming common smart decentralised power interrupter (DPI) that stops the HVAC device from running and consuming energy at all when the occupants’ desired temperature set point has been achieved. As master controller, the device will work again, once the temperature exceeds the individualized thermal comfort level of the occupants. Utilising power interrupters as the first step into smarting one’s building is not a prime technological challenge. It is more about studying the function of the device in depth and creating awareness of the tool’s merits - including its efficiency especially for non-inverted air condition systems. The paper cross-examines different experiments that have been conducted through different daytimes in residential area buildings, comparing the DPI with conventional air conditioners monitored by remote controls. As a conclusion, the device can save tremendous energy and CO2 for any conventional HVAC split unit.

Keywords: CO2-Saving, Power Interrupter, Green & Energy Efficient Buildings
1 Introduction

1.1 About the Decentralized Power Interrupter (DPI or short-cut: PI)

To gain thermal comfort and save CO$_2$, we can utilize available, but not marketed smart electricity power interrupters. These devices are simple smart thermostat systems to “out-smart” and balance the heat variation during day and night considering automatically any change in weather conditions. They do not switch to a lower push-out or ventilation mode like the inverter run units, but fully stop the run of the air conditioner, if the temperature falls below our individually keyed in set point. Once it rises beyond a desired upper limit (set point), it switches the split unit on again, and so forth.

The DPI is nothing like a rocket science. The device presents a simple thermostat wired into the circuit interrupting the flow of power once a certain set point is reached. In combination with mechanical ventilation tools, it can be used in almost all areas where temperature control in heating or cooling is required. In the following litmus test experiment it will be connected to a non-inverter split unit air-conditioner to control the temperature in the room.

Figure 1: Power Interrupter (Remote Control and Master Unit and Plug Socket)

In our experiment, the temperature of the device is set to a thermally comfortable level of 25.5°C. When the temperature at the position the occupant sits or sleeps reaches 25.4°C (hysteresis 0.1), the system automatically switches off the air conditioning device. When the room temperature exceeds 25.5°C, the device will automatically turn on the air conditioner again. The unit is compared to a remote-control run HVAC with 24°C as set point, because the DPI used showed a temperature of 1.5°C too low. This process is expanded continuously and automatically within the whole time span of the experiment.

Compared to the conventional sensor when the occupants switching the power “on” and “off”, the air conditioner works only on the level of the set temperature: Once it is reached, the DPI stops running and is basically silent. This will have an impact on the energy consumption of the household and can probably help to decrease global warming at least for all non-inverter split-units.

1.2 Problem Definition

Hot and humid temperatures in tropical and sub-tropical climate zones cause many residential houses, commercial buildings and offices to use air conditioning to gain thermal comfort, but at the same time increase operational costs compared with cooling by fans. The problem of the use of HVAC (A/C) in achieving thermal comfort is that it will result in excessively high energy consumption due to lack of accuracy of determining the temperature in case of the conventional A/C. Lack of temperature control and the use of...
air conditioners without inverter technology total not only in a high total electricity bill and carbon footprint. Rampant usage of A/C can also result in too cold temperatures, irritation of skin and diseases like flu or even asthma.

The lack of awareness about the importance of controlling energy usage in daily life might be a sign that the market is not yet matured to adapt to power interrupters. Despite numerous awareness campaigns related to energy saving by the government or the private sector, higher electricity prices are still not enough to have an impact on consumers. Hence, the device is not yet available anywhere in electrical outlets and the order from foreign countries for individual usages can be considered an ordeal.

As a result, the development of the Decentralized Power Interrupter for non-inverted split units to maintain the temperature of thermal comfort for cooling in a tropical country has not been studied. So it is the aim of this publication, to review the effectiveness of using power Interrupters for non-inverted split units in terms of energy savings. At the same time, the system is able to achieve more precise thermal comfort to the building occupants compared to a conventional air-conditioning.

1.3 Objectives
- To identify the energy saving potential while increasing thermal comfort of the occupant.
- To analyze the effectiveness of the decentralized Power Interrupter for non-inverted HVAC split units, and compare with conventional remote controls.
- Draw conclusions for future research and applicability of the decentralised Power Interrupter.

1.4 Hypothesis
An A/C fitted with Decentralized Power Interrupter will a) have a significant energy saving and b) create more satisfactory thermal comfort then the conventional remote controlled AC without the interrupter.

2 Literature Review
Marcus (1980) defined thermal comfort as a condition for humans to evaluate their environment either cold or too hot and the determination of the natural point of feeling uncomfortable avoidance (Zulkifli1999). For tropical countries, Busch (1990) carried out a pioneering field study for Thai offices in Bangkok and found that the neutral temperature or effective temperature for the air conditioned buildings and naturally ventilated buildings was 24.5°C and 28.5°C, respectively. A similar range of “neutral” conducive temperature was determined for a Malaysian School (Ibrahim Hussein, M Hazrin A Rahman (2009), based on PMV regression is 25.9°C with a comfort range between 24.4°C and 27 .4°C. Recently, Tan (2013: 28) suggested that “we should maintain the operative temperature below 28°C for a 90% acceptance”.

The trendy increase of temperature in offices and public cooled down areas also follows the in-part demise of the common dress code with suits and ties translatable into the 2011 policy by the Malaysian government requesting all state-owned buildings to set-point the temperature not lower than 24°C.
Abdul Rahman (1995) in his ground-breaking study found that the most comfortable indoor temperature in Malaysia (tropical region) for residential areas ranges even from 25.5-28°C narrowing down the general recommendation by World Health Organization (1990) ranging from 18-28°C. Similarly, UTM’s researchers Sabarinah Sh.Ahmad, Nor Zaini Ikrom Zakaria, Mohammad Shayouty Mustafa, Mohd Ghadaffi Shirat (2007) concluded that a 2.5°C range between 26.1°C and 28.6°C is optimum in tropical countries even for adopted people from Northern countries. Others and our own findings clearly confirm that the optimum residential area temperature for most tropical occupants in their privacy at its highest comfortable end should not exceed 28.6°C. As a conclusion, “the comfort band for the KL area for all building types is between 23.6°C and 28.6°C with an optimum medium temperature in Malaysian households of 26.1°C” with the upper space limit (USL) set at 28.6°C. Two reasons can be sorted out. 1) The lower cost when putting the highest setpoint in a tropical warm country. 2) The perception by people living in tropical regions is different from those in temperate and cold regions (Wang and Wong, 2007; Singh et al., 2009). Recent researches found out that implementing active easy measures with zero initial cost, such as raising the cooling temperature set-point or reducing the heating set-point around 1-2°C, may provide a tangible reduction in cooling and heating demand without compromising the thermal comfort (Itani et al. 2013, Kwong et al. 2014 & Du et al. 2015).

Different occupants may have different thermal comfort acceptances. Hence, different persons with different body mass indices leads to the optimum individual power interrupter set point banding. This banding was set by different Malaysian researchers usually between 24.5 and 28.6°C, whereas the common tropical ASHRAE standards set the banding of 4°C with the maximum of 26.5°C but without stating the maximum allowable RH rather than the common standard of 60%. One of the local certification tools in Singapore and Malaysia, the Green Mark states that the maximum end band with temperature is slightly lower at 26.2°C at a maximum RH of 70% (now 65%) which exceeds the standards of the Northern hemisphere by 10%.

Recent findings based on the renowned hx-diagram (Mollier 1921) state, however, that the optimum tropical temperature depends on the relative humidity which equals in the “felt” temperature as the sensation of our body cannot discern between RH and ambient temperature. Derived from the hx-diagram based Iphone application, it is hypothesised that for ANY temperature between 4 and 26.5°C the RH does not matter for an average BMI while sedentary, without overeating among a few other factors. The following table, derived from the tropical adaptation of Energy performance certificate reinstates this trend by the rainbow colour scale (Wagner 2014f.):
As a conclusion, prior to detailed investigations, we targeted a lower set point (25.5°C) and then a higher set point (28.2°C) as lower and upper space limit for our both experiments (A. and B.) expedited below.

3 Methodology
Our litmus test will focus on the effective usage of decentralized Power Interrupters for non-inverted split units in energy saving and at the same time to improve thermal comfort. Therefore, four parameters (temperature, relative humidity, energy consumption costs and CO2) will be analyzed in this study. This study will compare the effectiveness between decentralized Power Interrupters for non-inverted split units and the same device run by a typical conventional remote control.

The research gadgets consist of the Power Interrupter, Temperature and Humidity Logger, Power Data Logger and the Minitab 15 as statistical software application.

In this pilot study, 2 test rooms in 2 similar residential houses were used:

A. 1 night spot check how the PI periods work in detail and how much energy saving can be estimated during the night time.

B. 5 days longitudinal study: The Sample Terrace House is located in a typical suburban area south of Kuala Lumpur.

4 Findings
The weather conditions in our 5 days comparison are typically sunny-cloudy with mostly overcast skies. Figure 3 shows 5 days without interception of rain with the consequence that as a clear tendency the days become slightly hotter and less humid with less variations:
The most important finding in terms of individualized thermal comfort shows that the PI produces the desired temperature with a variation of 0.5°C, whereas the device without PI generates 2°C lower temperatures with significantly higher standard variations.

It is evident that at the same set point the temperature gained with the DPI (black line) is not only more reliable with a lower standard deviation than the conventional air conditioner (red line). It is also plain to see that the DPI (black line) is always within the chosen thermal comfort level, as the RH represented in the chart below is effectively monitored.
By default, the HVAC without PI keeps on producing values that can be considered as too dry for optimum tropical standards which recently echoed in the upper space limit for RH heralded by the official certification tool with max. 70% and (since 2015) 65% in Singapore and Malaysia (Green Mark 2013, 2015f.).

The detailed view in our alternative experiment with a set point of 28.2°C that appeals the maximum Malaysian thermal comfort standard (e.g. Zabarina et al. 2007) suggests that depending on the base temperature between 29 and 31°C after a lead time of 30 to 60 minutes the PI will refrain the first time from running on. That means obviously: the colder the set point, the longer it takes any device to reach the desired temperature (and the “default” RH). After the lead time, the PI typically generates cycle times of about 15 minutes equal “off” and “on” durations. The test night when the temperature was recorded every 10 seconds echoed in 14 cycles.
What happens after 6h of operation? Since the condominium building is not insulated at all and the test room is facing sunlight from sunrise until 4 p.m., the heat stack effect causes the walls to keep the heat even in the early morning hours when after 6h of operation the PI remains switched off. The temperature converged again to a level where at least a stand fan is required to gain thermal comfort of at least 26.5°C.

Comparing the daytime mode, the RH variation when using the PI is almost the same. After the first period when the RH is decreased to an unnecessary level of 50%, it immediately leaps back to 70% during the 15 minutes standstill periods, and removes the RH again constantly to 61% during its operation periods.

As a conclusion, it is very questionable whether the dehumidification in conventional HVACs has been engineered equivalently to tropical standards at all. This has also severe
cost implications, because dehumidification is an expensive function which, however, cannot be detached from the cooling mode. Maybe it is because the accepted higher humidity for humans might be detrimental for moulds which only could be defeated by the non-existing mechanical cross ventilation.

During 4 of 5 days, the conventional without PI is clearly on the loose during the night time. Only the day 4 results look more equal. Looking into the electricity consumption respectively the carbon footprint, it turns out that the PI can save around

\[
\frac{1}{4} \text{ of the electricity consumption during the daytime:}
\]

In total, over 5 days, the total electricity consumption for air conditioning with Power Interrupter was 98.8956 kWh while the A/C with conventional remote control was recorded
at 123.3836 kWh (Hairie 2013). The total energy savings over 5 days was 24.488 kWh. This value is almost equal to the electricity consumption for 1/5 days. Furthermore, without using only one A/C in a 4 room double storey building it consumes up to 75% of the overall energy. During the early evening, the overall results of the 5 days comparison are echoed in the following 1 hours spot check that might already indicate the cumulated savings (43/26 minutes = only 60% operation time):

ON/OFF Cycles

<table>
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<tr>
<th></th>
<th>ON</th>
<th>OFF</th>
<th>minutes ON</th>
<th>Min. OFF</th>
<th>Cumulated min. ON</th>
<th>Cumulated OFF =&gt;SAVINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.15</td>
<td>19.23</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>19.32</td>
<td>19.41</td>
<td>0.09</td>
<td>0.15</td>
<td>0.17</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>19.56</td>
<td>20.05</td>
<td>0.09</td>
<td>0.19</td>
<td>0.26</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>20.24</td>
<td></td>
<td></td>
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</tbody>
</table>

The figure shows that the energy saving is in a region of about 40%, as we can assume that switching on and off does not trigger extraordinary more consumptions and the life span of the compressor (that resembles the one of an ever switching on-and-off mode of a refrigerator) will not be negatively affected.

5 Conclusion

1. The usage of decentralized power interrupters showed proven record to contribute to energy saving for mass customised homes. The saving during the day for the initial tests was reported at 29% (daytime) and altogether 62% during the night time in conventional non-green buildings with no proper insulation.

2. Compared to conventional air condition thermostats, which did not supply the requested temperature reliably, the usage of decentralized power interrupters provided 24/7 thermal comfort. At the same time, the relative humidity of the device under testing seemed to adhere to the higher Green Mark standards of not exceeding 70%.

3. The power interrupter is easy to install, avoids the hassle of switching on and off A/Cs and furthermore, appeals to a greener lifestyle with higher accepted temperatures. As the “on” and “off” cycles are in about 15 minutes intervals, occupants might not be troubled by the changing mode of operation and silence.

4. The decentralized power interrupters allows short term payback returns, if the device is successfully marketed and certified in tropical countries.

5. Based on the findings demonstrated above, in the future the following needs to be tested:
   - Different set points and different hystereses (0.1-0.5 °C).
   - Experiments with different ACs incl. inverter (how many energy savings and power interruptions?)
In order to check the effect on the life span of the compressor, a longitudinal study is required.

1. If the use of the power interrupter helps in saving energy while maintaining a level of thermal comfort and indoor CO₂, despite higher complexity this technology should be utilised and tested by not only split unit systems, but also to the others types air-conditioning systems.

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OPTIMISATION OF SOLAR HOT WATER SYSTEMS FOR DIVERSE BUILDING TYPES UNDER A HOT CLIMATE

Kheira A. Tabet Aoul\textsuperscript{1}, Ahmed Hassan\textsuperscript{2} & Hassan Riaz\textsuperscript{3}
Architectural Engineering Department, United Arab Emirates University, Al Ain, UAE,
\textsuperscript{1}Kheira.Anissa@uaeu.ac.ae, \textsuperscript{2}Ahmed.Hassan@uaeu.ac.ae & \textsuperscript{3}hassanuaeu59@uaeu.ac.ae

Abstract: The integration of solar energy systems in buildings is an established and increasingly sought strategy, used in multifaceted ways as an alternative energy source that carries environmental, social and economic benefits. Solar water heating is one application resulting from the conversion of solar radiation into heat. Solar Water Heating Systems (SWHS) have proven to be cost efficient in various building types inclusive of residential, commercial and industrial in colder climates however, their effectiveness in hot climate is not well studied. This paper assesses the parameters influencing the performance of solar hot water production systems for different building applications under hot climate of Abu Dhabi, United Arab Emirates. The analysis is conducted numerically through a thermal model developed in TRNSYS. The optimal parameters of the collector tilt angle, collector type and the ratio of collector aperture area to building area are determined for different building types.

Keywords: Solar water heating systems, TRNSYS software, Parametric optimization, Energy harvesting, collector tilt angle, area, building types
1 Introduction
The total world energy consumption is projected to increase to 198,654 ZW (zetta watt) by 2030 compared to 82,919 ZW in 1980, showing an increase of more than two folds in the last 50 years (U.S Energy Information Administration 2009, International Energy Agency 2014). Accordingly, the energy consumption reached 140 GWe in 2015 in the of Gulf Cooperation Council countries (Greenpeace 2013) making them one of the highest energy consumers per capita in the world. The United Arab Emirates (UAE) consumed 11,044 kWh per capita in 2010 (The world bank electric power consumption 2013) resulting in per capita carbon emissions being two times higher than the developed countries (Kazim 2007).

Worldwide, the building sector leads the energy consumer’s list with 40% followed by industrial activities with a 37% share of total energy consumption (Abdelaziz 2011), The European parliament and the council of the European Union 2010). Out of the total energy consumed in buildings, space and water heating needs can be as high as 81% in cold climates (U.S. energy information administration 2015) and 30% in hot climates (Kempener 2015). This large amount of energy usage for space and water heating in buildings contributes to carbon dioxide emissions, heightening the climate change effect (U.S. Environmental Protection Agency 2016).

The UAE housing stock consumes 33% of the total energy demand out of which, the highest portions is devoted to HVAC and domestic hot water (DHW) accounting for the 55% of the total energy utilization (Radhi 2009, Global solar thermal energy Council 2010). The industrial sector is also a potential heat consumer in UAE requiring heat in the temperature range of 60°C to 260°C. The analysis of thermal energy need in industrial sectors demonstrates that solar thermal energy has massive applications in low (<150°C) medium (150°C-400°C) and high (> 400°C) temperature ranges (Kalogirou 2003, IRENA 2015).

The immense solar radiation available in the region at large and UAE in particular offers a promising source of heat supply for the housing and industrial sector. The measured on-site solar energy was found to be 18.48 MJ/m²/day based on yearly average data (Islam 2009) with peak intensity varying between of 1100 W/m² and 900 W/m² in depending season (Hasan 2016 (a), Hasan 2016 (b)). Such stronger solar radiation has been extensively used by an array of 84 thermal collectors supplying 24,000 liters of hot water per day 60 °C in Dubai-UAE (Global solar thermal energy Council 2010). Previous studies conducted in UAE revealed that abundant availability of solar radiations in the region render SWHS a more efficient and economical option (Ghaith 2014). However, existing studies in the country focus on experimental findings with least consideration of performance optimization of the system to fully exploit the abundantly available thermal energy.

Hence, this study aims at parametric optimization of solar hot water production systems for different building applications in Abu Dhabi, United Arab Emirates (UAE) by employing TRNSYS (A transient system simulation program 2004). The parameters considered include tilt angle, surface area and the collector type.
2 Methodology

A transient thermal model was developed in TRNSYS integrating the solar thermal collector, auxiliary heating source and the water storage to provide hot water demand for different building types with variable solar hot water needs. Simulation studies were carried out to assess the effectiveness and contribution of SWHS in meeting specific hot water demand in different building types under the specific hot weather conditions of Abu Dhabi, UAE. The optimal parameters of collector inclination angle (tilt angle), collector scaling (aperture area to building area) and collector type were determined for particular demand side water temperature, representative of different building types.

2.1 Simulation Model Set Up

The detailed interface diagram of the TRNSYS model is shown in Figure 1. The weather data of interest is processed (weather) as per required resolution to feed into the thermal model (collector). A feedback ON-OFF control loop is in place (controller) between the collector outlet and demand side temperature (Tank) to trigger inlet water flow through collector as required. The control loop is meant to only start and stop water flow sensing the demand (tank temperature) and available resource (radiation). The control loop possesses inherent constraint in terms of optimal water flow rate with varying weather conditions, which is not considered in current simulations. The flow rate can be optimized through simulation findings at a later stage.

The flat-plate solar collector model was based on the Hottel–Whillier steady-state model (Klein 1975) which predicted the heat gain rate as mentioned in equation 1;

\[ Q_{ch} = A_{ap} \times I_{ssh} \times \alpha \times \beta \]

Figure 1: Simulated diagram generated by TRNSYS (A transient system simulation program 2004)
The relation describes the heat gain in terms of the aperture area of the collector \( A_c \), overall energy gain efficiency factor \( f_{r,k} \) total solar radiation gain \( I_{ti} \) and collective losses \( U_{c,k} \). Energy efficiency factor of the collectors is calculated using equation 2 which is and exponential function of the aperture area and thermal capacity of the collector;

\[
f_{r,k} = \frac{n_c m_c c_{pc}}{A_c U_{c,k}} \left( 1 - e^{-\frac{n_c m_c c_{pc}}{A_c U_{c,k}}} \right)
\]

\( (1) \)

The \( (\tau \alpha) \) term is product of transmittance and absorptance of the absorber plate due to incident beam-radiation, incident diffuse-radiation, and ground reflectance, respectively. The \( (\tau \alpha)_b, (\tau \alpha)_d \) and \( (\tau \alpha)_g \) are calculated by the trigonometric co-relation considering collector relative position to the incoming solar radiation as given in equation 3;

\[
(\tau \alpha) = \frac{l_b (\tau \alpha)_b + l_d \left( \frac{1 + \cos \beta}{2} \right) (\tau \alpha)_d + r_g l_t \left( \frac{1 - \cos \beta}{2} \right) (\tau \alpha)_g}{l_T}
\]

\( (2) \)

\( (U_{c,k}) \) is overall loss-coefficient (Klein 1975) as a combined effect of the top and bottom loss-coefficients accounting for both convection and radiation losses. These losses are calculated in the terms of number of glass covers \( n_g \), collector fin efficiency \( f_c \), number of collectors \( n_c \), Stefan Boltzmann’s constant \( \sigma \), emissivity of glass cover \( \varepsilon_g \), absorber plate emittance \( \varepsilon_p \) and loss coefficients for edges and bottom \( U_{be} \) as calculated in equation 4.

\[
U_{c,k} = \frac{3.6 \left( c \left( \frac{T_{av,k} - T_a}{n_g + f} \right) \right)^{0.33} + \frac{1}{h_w} + \frac{3.6 \sigma \left( T_{av,k}^2 + T_a^2 \right) \left( T_{av,k} + T_a \right)}{1 + \frac{2 n_g + f - 1}{\varepsilon_g + 0.05 n_g \left( 1 - \varepsilon_p \right)}}}{n_g}
\]

\( (3) \)

The thermal storage tank is designed with an immersed coiled heat exchanger, with five segments for thermal lamination. The temperature of hot water \( T_{hw2} \) at the outer side and average temperature \( T_{hwa} \) at inner side of hot water tank were calculated by using the equations 5 and 6 (Solar-Energy Laboratory).
\[ \frac{dT_{\text{tank}}}{dt} = \frac{Q_{\text{in,tank}} - Q_{\text{out,tank}}}{c_{\text{tank}}} \]  
(5)

\[ \frac{dT_{\text{HX}}}{dt} = \frac{Q_{\text{in,HX}} - Q_{\text{out,HX}}}{c_{\text{HX}}} \]  
(6)

Where \( Q_{\text{in,tank}} \) and \( Q_{\text{out,tank}} \) are dependent on the temperature of heat exchanger, ambient temperature and solar irradiation; \( Q_{\text{in,HX}} \) and \( Q_{\text{out,HX}} \) are dependent on inlet fluid temperature and temperature of tank. The temperatures \( T_{\text{hw2}} \) and \( T_{\text{hwa}} \) are calculated by opting equations 7 and 8.

\[ T_{\text{hw2}} = \left( T_{\text{hw1}} + \frac{b_{\text{ave}}}{a} \right) e^{at} - \frac{b_{\text{ave}}}{a} \]  
(7)

\[ T_{\text{hwa}} = \frac{1}{ad}(T_{\text{hw1}} + \frac{b_{\text{ave}}}{a})(e^{at} - 1) - \frac{b_{\text{ave}}}{a} \]  
(8)

Where \( a \) and \( b \) are the coefficients of the differential equation in the form \( dT/dt = aT + b \) and \( b_{\text{ave}} = b_{\text{ave}} \).

3 Weather data

The typical meteorological yearly weather data for Abu-Dhabi is employed carry out simulations. The weather data is categorized into hot, mild and cold season based on ambient temperature. Three sample days are taken to describe daily data for each season.

Figure 2A shows global solar radiation intensity (G) and average ambient temperature (\( T_{\text{amb-avg}} \)) of three sample days of extremely hot weather. The values of G were 1104 MJ/day, 1104 MJ/day and 1080 MJ/day respectively for the sample days with the coefficient of variation (CV) of 1% which depicts the consistency of weather conditions.

The average of ambient temperature remained stable within sample days with the average value of 37°C. Similarly, Figure 2B and 2C show global solar radiation intensity (G) and average ambient temperature (\( T_{\text{amb-avg}} \)) of mild weather and cold weather respectively. The values of G were 1008 MJ/day, 1008 MJ/day and 1032 MJ/day for mild conditions and 960 MJ/day, 864 MJ/day and 864 MJ/day for cold conditions with the coefficient of variation (CV) of 1.1% and 4.9% respectively. The average of ambient temperature was constant for the targeted days with a value of 27°C for mild and 20°C for cold weather.
4 Parametric Influences

Parametric influence of tilt angle, collector scale (aperture area), collector type and demand side water temperature (building type) were assessed.

4.1 Tilt angle

In the current study, the performance of the solar collector is investigated for pitched roof with a varying collector slope ranging from 12° to 36°. The simulation revealed that the best performance was achieved at the angle of 24° with maximum heat gain value of 194,304 MJ/day as shown in Figure 3. The results are in agreement with the previous findings for the geographical location of the experiment, i.e. Abu Dhabi (24°N, 55°S), this solar angle yields maximum solar irradiance (Hasan 2016, C). After optimizing pitch angle, the performance of collectors installed at pitched roof (24°), flat roof (0°) and vertical wall (90°) are compared for various building types as shown in Figure 4. The results show that the wall-mounted systems always required higher collector area per building area thus representing the least energy performance. It can be seen that the sloped roof and flat roof integrated thermal collector’s performance comparably which is understandable as the latitude is very low at the site. Comparing building types, the school buildings required highest collector area per building area mainly due to higher occupant’s load. The fundamental parameters of the building and solar collector are presented in Table 1 to determine the collector area required per building area for various building types.
Figure 3: Energy contribution from solar collector and auxiliary source with varying tilt angle

The required water and temperature ranges (Walter 2015) were used to calculate the hot water demand. This energy demand varies for different types of buildings depending upon their utility.

\[ E = mC_p \Delta T \]

Considering the average data, throughout the year, hospitals need hot water of 325 gallon/day at the temperature of 65°C. The proposed system in this research, for sample days considered, is capable of delivering 55 gallon/day, 48 gallon/day and 42 kg/day with the required temperature while extra water of 269 gallon/day, 276 gallon/day and 282 gallon/day will be covered by an auxiliary source in hot, mild and cold weather conditions respectively. Second in hot water consumption, school required 87.5 gallon/day of 65 °C. The suggested system is supplying 53 gallon/day, 49 gallon/day and 41 gallon/day with needed temperature while additional water demand of 34 gallon/day, 38 gall/day and 46 gallon/day will be satisfied by an auxiliary mean in hot, mild and cold weather conditions correspondingly. Medium consumers like pressing and bleaching businesses required hot water of 25 gallon/day with temperature range of 100°C. Our recommended system has a potential of delivering 20 gallon/day, 17 gallon/day and 15 gallon/day with required temperature while remaining water need of 5 gallon/day, 8 gallon/day and 10 gallon/day will be met by an auxiliary source in hot, mild and cold weather conditions consecutively.
Figure 4: Variation of collector area for fixed building area at tilt angle of 0°, 24° and 90°

Table 1: Solar collector area required to meet per person and overall building demand of hot water

<table>
<thead>
<tr>
<th>Building type</th>
<th>Scale (m²)</th>
<th>Density (m²/p)</th>
<th>Population (p)</th>
<th>Water Demand (g/p-d)</th>
<th>Total Demand (g/p-d)</th>
<th>T (°C)</th>
<th>Solar Collector Area (g/m²)</th>
<th>Total Area (m²)</th>
<th>Collector to Building Area Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>20000</td>
<td>60</td>
<td>328</td>
<td>60</td>
<td>19680</td>
<td>45</td>
<td>67</td>
<td>293</td>
<td>0.01</td>
</tr>
<tr>
<td>Hospital</td>
<td>20000</td>
<td>73</td>
<td>273</td>
<td>325</td>
<td>88725</td>
<td>65</td>
<td>28</td>
<td>3168</td>
<td>0.15</td>
</tr>
<tr>
<td>School</td>
<td>20000</td>
<td>6</td>
<td>3280</td>
<td>87</td>
<td>285360</td>
<td>65</td>
<td>26</td>
<td>10975</td>
<td>0.54</td>
</tr>
<tr>
<td>Office</td>
<td>20000</td>
<td>30</td>
<td>656</td>
<td>50</td>
<td>32800</td>
<td>65</td>
<td>26</td>
<td>1261</td>
<td>0.06</td>
</tr>
<tr>
<td>Textile Industry</td>
<td>20000</td>
<td>30</td>
<td>656</td>
<td>25</td>
<td>16400</td>
<td>100</td>
<td>9</td>
<td>1822</td>
<td>0.09</td>
</tr>
</tbody>
</table>

4.2 Collector type

The main thermal collector types are compared in terms of energy performance which are predominantly employed in buildings as shown in figure 5. It is observed that the evacuated tube collector performed better followed by thermosiphon and flat plate collector while the CPC performed the worst. The reason can be explained as the evacuated, thermosiphon and flat plate collector are low temperature collectors and can be optimal for low temperature energy demand of the buildings. The CPC are only optimized at higher concentrations and higher temperature requirements from 250°C-400°C which was not studied in this case.
5 Energy performance

The achieved simulation results for 8670 hours (1 year) yielded variations in the hot water temperature at the exit of heater as shown in Figure 6. This temperature ranged between 9–100 °C with the mean value of 54.5 °C. To meet a certain temperature demand, additional water heating was produced using auxiliary source.

6 Conclusion

This study has examined the energy performance of SWHS in various building types under the hot climate of Abu Dhabi, through TRNSYS simulation model to optimize the thermal collectors. An optimal tilt angle of 24 ° is identified to exploit the maximum potential of the system for the studied location, Abu Dhabi, UAE. In terms of SWHS tilt angle, the wall-mounted collectors are the least effective compared to flat roof and pitched roof-integrated systems. Additionally, the collector area required per building area shows that the schools
exhibit the highest collector area compared to building area. Additionally, the results indicate that in each case an auxiliary heating source is required to compensate for the diurnal temperature fluctuation as well as provide a continuous supply of hot water in the absence of solar radiation.

Acknowledgements
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Nomenclature
SWHS solar water heating systems
DHW domestic hot water
$A_c$ total collector-array aperture area (m$^2$)
$C_{HX}$ heat-capacitance of coiled heat-exchanger inside calorifier (kJ/K)
$C_{pc}$ specific heat of collector fluid (kJ/ (kg K))
$C_{tank}$ heat capacitance of calorifier tank (kJ/K)
$f_c$ collector-fin efficiency factor
$f_r$ overall collector heat-removal efficiency factor
$I_b$ incident-beam radiation per unit area (kJ/ (h m$^2$))
$I_d$ horizontal diffuse radiation per unit area (kJ/ (h m$^2$))
$I_t$ total horizontal radiation per unit area (kJ/ (h m$^2$))
$I_i$ total incident-radiation on a flat surface per unit area (kJ/ (h m$^2$))
$m_c$ collector fluid mass-flow rate (kg/h)
$n_c$ number of identical collectors that are mounted in series
$n_g$ number of glass covers
$Q_c$ rate of heat gain of total collector array (kJ/h)
$Q_{in, HX}$ rate of heat gain of a coiled heat-exchanger inside the calorifier (kW)
$Q_{in, tank}$ rate of heat gain of calorifier tank (kW)
$Q_{out, HX}$ rate of heat loss of coiled heat-exchanger inside the calorifier (kW)
$Q_{out, tank}$ rate of heat loss from calorifier tank (kW)
$r_g$ ground reflectance
$T_a$ ambient temperature (°C)
$T_{av}$ average collector-fluids temperature (°C)
$T_{hw}$ hot-water average temperature inside tank (°C)
$T_{hw1}$ hot-water initial temperature (°C)
$T_{hw2}$ hot-water final temperature (°C)
$T_{HX}$ temperature of coiled heat-exchanger inside the calorifier (°C)
$T_i$ temperature of fluid entering the collector (°C)
$T_p$ collector-plates temperature at stagnation (°C)
$T_{tank}$ temperature of calorifier tank (°C)
$U_{be}$ loss coefficient for bottom and edge of collector per unit area (kJ/ (h m$^2$ K))
$U_c$ overall loss-coefficient of collector per unit aperture area (kJ/ (h m$^2$ K))
$CV$ Coefficient of variation (%)

Symbols
$\alpha$ absorptance of absorber plate
$\epsilon_g$ emissivity of glass covers
$\epsilon_p$ absorber plate emittance
$\sigma$ Stefan–Boltzmann constant ($5.6697 \times 10^{-8}$ W/ (m$^2$ K$^4$))
$\tau$ transmittance of absorber plate
$\Delta t$ simulation time-step (h)
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SESSION II - SUSTAINABILITY
THINKING BEYOND ZERO-ENERGY BUILDINGS: INVESTIGATING SUSTAINABILITY ASPECTS OF TWO RESIDENTIAL URBAN FORMS IN UAE

Khaled Galal Ahmed

1 Arch. Eng. Dept., College of Engineering, United Arab Emirates University, UAE, kgahmed@uaeu.ac.ae

Abstract: Most of the debate about sustainable mass housing concentrates on energy performance on the building scale with increasing attention devoted to zero-energy experiences. This research aims to jump over this focus and to rather investigate on the influence of urban form on energy efficiency of neighborhoods. This research has investigated sustainability attributes of urban forms in two neighborhoods in Al Ain city in Abu Dhabi Emirate, UAE. The first one represents the conventional urban forms based on the neighborhood theory; while the other represents a new ‘claimed to be sustainable’ design experience. Al Ain city has been selected as a locus for this investigation as it is currently considered as a model for green/sustainable cities in UAE. In order to address the research problem, and through literature review about the common principles of sustainable urban form, a conceptual framework has been initiated in order to facilitate the assessment of the urban forms of the two selected urban communities. This conceptual framework encompassed the following principles: density, accessibility, choice, mobility, mixed use, adaptability, local autonomy, and environmental quality. Some measurable indicators have been developed for each of these principles. The results of the analysis of the two conventional and ‘sustainable’ case studies have divulged positive and negative aspects relevant to urban forms, which have in turn revealed the potentials for actions that could shape a better future path towards realizing sustainable urban form of local urban communities in UAE.

Keywords: Sustainable, Urban Form, Housing, Urban Communities, UAE.
1 Introduction

Sustainable urban form is a critical means to realize sustainable urban housing. It is defined as the concept of attaining sustainable city through configuring its shape, function, and adaptably to change over time (Burton, Jenks and Williams, 2013 and American Society of Landscape Architects, 2015). Handy and Niemeier (1997) claim that sustainable urban form is intensely relevant to the residents’ behavior within the built environment that it develops, thus, it stimulates residents to be more vigorous and to positively utilize urban spaces.

In relation to the process of producing the urban form, Neuman (2005) argues that sustainable urban form manifests both the process and the product that emerges from it. The formation process of sustainable urban form integrates various sustainability features of cities in living, consuming, and producing. Accordingly, comprehending the influences of a specific urban form on environment and social issues necessitates understanding the interrelated, inclusive and adaptive processes producing such urban form. One cannot define a single urban form to be sustainable. Rather, there are various urban forms that each of them can suit a specific context depending chiefly on the traits of an area and its associated development objectives and plans. In general terms, an urban form can be claimed sustainable when it could be responsive to the carrying capacity of the natural and the built environment, could provide a friendly living setting and when it could achieve social justice (Frey, 1999). Jenks and Burgess (2000) maintain that achieving sustainable urban form entails developing compact built-up area with appropriate population densities in order to boost economic, social and cultural activities. Compactness and concentration of urban functions within the urban area help pursuit the environmental, social and economic sustainability benefits. Urban intensification is pointed out as a major approach for achieving compactness and usually achieved through using urban land more efficiently by increasing the density of activities (Jabareen, 2006).

On the other hand, sustainable urban form is conventionally measured by: how the urban form affects vitality, the degree to which the settlement form fits the requirements of people, how able people are to access activities/services, how much control people have over services, activities, and urban spaces (Jones and MacDonald, 2004). In a more categorized manner Allen (2009) outlines four facets that shape the sustainable urban form. First is the environmental dimension, which relates to the influence of urban production and consumption on the integrity and vigor of the urban area and its carrying capacity. Second is social dimension that entails equity, inclusiveness and adequacy of urban development, as this would endorse social justice that supports the livelihoods of residents in local communities. Third is the economic dimension, which entails the ability to exploit both local and regional resources for the welfare of the whole community. Fourth, is the political dimension, which deals with the quality of urban governance in controlling the decision making processes of different actors among the former three sustainable urban form dimensions. As for this research, the focus is going to be on the environment dimension but keeping in mind its interrelations with other dimensions.

Frey (1999) emphasizes three aspects that distinguish the sustainable urban form of a neighborhood, namely, accessibility, proximity and functional mix. Provision of public transport has been proven to be the most economical way to facilitate mobility in a city, which in turn necessities a modular city context composed of urban ‘cells’ or ‘proximity units’. The interrelationship of people, transport and service is thus considered the core for the microstructure of the city. Therefore, the city physical structure may well be hierarchical, from neighborhood, the smallest ‘building block’ or ‘unit’ of which the city is
made up, to district to city in terms of catchment areas for services and facilities of different caliber. Accordingly, achieving sustainable urban form requires the consideration of its principles on different urban levels: neighborhood, district, and city.

Jabareen (2006) claims that there is a noticeable consensus among researchers that mixed use plays a vital role in realizing sustainable urban form. Heterogeneous zoning permits land uses to locate in close proximity to one another to homes and thereby decrease the travel distances between activities. Mixed land use entails the diversity of activities and services such as residential, commercial, industrial, recreational and so on.

Several research indicated that the sprawl urban form induces car oriented lifestyles and consequently entails higher urban management costs and is accompanied by intensive travel movements and associated negative environmental effects (Coppolaa et al, 2014). As for urban neighborhood, population density should be sufficient for supporting the provided services and facilities. Neighborhood shared amenities and public transportation nodes should be located within walkable distances from houses. It is also preferable to gather the local services and facilities centrally around the transport node because this will create a vivid and mixed-use central place (Frey, 1999).

Finally, Dempsey et al (2012) mentioned that community stability and sense of belonging to place were found to be influenced by not only non-physical aspects such as feelings of satisfaction with the neighbourhood, but also with a number of physical form features including: density, type of accommodation and its location in relation to surrounding services and facilities, public transport and the city center.

2 Research Aim and Method
This research is concerned with investigating sustainability attributes of urban forms on both the conventional and what has been recently claimed to be ‘sustainable’ neighborhoods. Al Ain city in Abu Dhabi Emirate has been selected as a locus for this investigation as it is currently being officially proclaimed as a model for green/sustainable cities in UAE. To address the research problem a conceptual framework has been initiated in order to facilitate the assessment of the urban forms of two selected urban communities in Al Ain; Al Salamat and Shaubat Al Wuttah representing the conventional and the sustainability-orientated planning respectively. Meanwhile, the proposed conceptual futuristic scenario for achieving sustainable urban form for residential development in UAE is to be initiated through the interpretation of the outcomes of the investigations of these two case studies.

3 Conceptual Framework for Sustainable Urban Form
Based on in-depth review of the above-mentioned references in the Introduction section, a proposed sustainable urban form conceptual framework has been developed (Table 1). This framework encompasses the following principles: density, accessibility, choice, mobility, mixed use, social mix, adaptability, local autonomy, and environmental quality. Some measurable indicators have been established for each of these principles to ease the process of the qualitative assessment of the degree of attainment of each of these principles. It should be acknowledged here that despite the attempt to make it as comprehensive as possible, still this framework might have missed out some of the principles and/or indicators. Also, some of the suggested indicators might change from one context to the other based on the applied local regulations.
Table 1: The Conceptual Framework for Neighborhood Sustainable Urban Form

<table>
<thead>
<tr>
<th>Principal</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td>Variety of house types.</td>
</tr>
<tr>
<td></td>
<td>Sufficient density to support respective and viable local services and facilities and to support public transport.</td>
</tr>
<tr>
<td></td>
<td>Core may have an area of about 1 ha.</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td>Local provision of daily amenities, services and facilities.</td>
</tr>
<tr>
<td></td>
<td>Ease of access to local services and facilities by less mobile category.</td>
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<tr>
<td></td>
<td>Permeable spaces and friendly landscaping.</td>
</tr>
<tr>
<td></td>
<td>Minimizing physical and psychological barriers.</td>
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<td></td>
<td>Proper signage system.</td>
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<td></td>
<td>Access to district and city centres through efficient public transport.</td>
</tr>
<tr>
<td></td>
<td>Public transport stops/nodes within walking and cycling distance (10 min walk max-600m).</td>
</tr>
<tr>
<td></td>
<td>Public transportations should have traffic priority and exclusive lanes.</td>
</tr>
<tr>
<td></td>
<td>Higher concentration of services and facilities around public transport nodes.</td>
</tr>
<tr>
<td><strong>Choice</strong></td>
<td>Hierarchy of services and facilities of different capacity and scale.</td>
</tr>
<tr>
<td></td>
<td>Choice of mode of mobility.</td>
</tr>
<tr>
<td></td>
<td>Catchment areas overlap with other neighbourhoods.</td>
</tr>
<tr>
<td></td>
<td>Various housing units/buildings in sort and design.</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td>Safe, shaded, well-lit and pleasant pedestrian routes leading to transport nodes, services and facilities.</td>
</tr>
<tr>
<td></td>
<td>Safe road crossing and buffer zones.</td>
</tr>
<tr>
<td></td>
<td>Safe cycling routes leading to transport nodes, services and facilities.</td>
</tr>
<tr>
<td></td>
<td>Allocated bus lanes and priority in traffic rules to be given to cyclists over car users.</td>
</tr>
<tr>
<td></td>
<td>Availability of effective coordinated, fast, comfortable, and inexpensive public transport providing access to district and city centres</td>
</tr>
<tr>
<td></td>
<td>Well designed, sheltered bus stops every 300m.</td>
</tr>
<tr>
<td></td>
<td>Road hierarchy.</td>
</tr>
<tr>
<td></td>
<td>Calming traffic inside neighbourhood.</td>
</tr>
<tr>
<td></td>
<td>Car-parking for locals and no car parking at neighbourhood centres.</td>
</tr>
<tr>
<td><strong>Mixed use</strong></td>
<td>Walkable day-to-day convenient shopping and community facilities.</td>
</tr>
<tr>
<td></td>
<td>Multi use of buildings for commercial and housing.</td>
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<td>Higher concentration of services and facilities around public transportation nodes in walking and cycling distance from residents’ front doors.</td>
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<td>Allowing for appropriate workplaces.</td>
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<tr>
<td><strong>Adaptability</strong></td>
<td>Ability to change and expand in response to changing socio-economic conditions without major upheaval.</td>
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<td>Adaptability should be achieved on both the housing unit and urban scales.</td>
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<tr>
<td><strong>Local autonomy</strong></td>
<td>Convenient retails (day to day).</td>
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<td></td>
<td>Small businesses.</td>
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<td>Production of food.</td>
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<td>Ability of individuals and the community to shape their own environment.</td>
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<tr>
<td><strong>Environmental quality</strong></td>
<td>Private and semi-private green areas for residential units.</td>
</tr>
<tr>
<td></td>
<td>Plantation of public open spaces and streets.</td>
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<td>Clamed and outside traffic (pedestrian-oriented environment).</td>
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<td>Adequate size of population.</td>
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<td>Open and accessible public spaces.</td>
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<td>Reuse of existing resources.</td>
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4 Analysis of Urban Form of Al Salamat: The Past Experience

Al Salamat is a public neighborhood that was developed in 2000. It is located approximately 21 km west of Al Ain city center (Fig. 1).

Density: The site area is about 132.5 ha. It contains 166 single family houses with plot dimensions of 45 m x 45 m. Gross density is about 11.3 person per hectare which is a remarkably low density mainly resulted from the adopted sprawl design of a car-oriented urban form (Fig. 1 and 2).
Accessibility: As for accessibility, where urban design should respect the walking distances from houses to services and facilities, in Al Salamat only one nursery serves a residential block and the primary schools serve only one and half of the blocks. Students who live by the edge of the neighborhood need to walk double the standard distance (1.25Km). Private cars and school buses are commonly used to commute students. Middle schools are located in the other neighborhoods (1.8 Km away). Meanwhile, secondary schools are located in Al Yahar District (7 Km away). Retail shops are located by the edge of the neighborhood and besides each mosque within the residential blocks, which allow a kind of multi-purpose trips. Other planned services like clinics, playgrounds and parks are not developed yet, apparently because of the low population density that negatively affects the economic vitality of the neighborhood. It is also noticed that some inappropriate locations of the internal cross roads cause more trip lengths.

![Figure 1: Al Salamat Community and its land use.](image1)

![Figure 2: Low density in Al Salamat.](image2)
**Choice:** As choice means that the design should provide a variety of services that create local options for shopping, schooling and socializing without reliance on car, it is noticed that the existing services/facilities in Al Salamat are limited in number and qualities. There is also lack of pedestrian walkways and sufficient bus station while the cycling lanes are totally absent. The neighborhood is originally designed to have more services that would help improve choice such as a clinic, public park and more retail shops but only if density would support such economic activities and services.

Choice also means providing various housing units/buildings in sort and design. But, there is no diversity or varieties in housing types in this neighborhood. Only some inhabitants managed to change/extend their houses over time. The originally proposed master plan has assigned zones for residential apartment blocks that would, if implemented, enrich housing types diversity and avail choices.

**Mobility:** For the pattern of movement the urban design should consider the proper distribution of activities locations that minimizes trip lengths, and to be well serviced by public transportation. In Al Salamat, as mentioned above, the catchment distances compel residents to use their own cars. Also, some inappropriate locations of services and houses require more trip lengths. Additionally, while the design should foster walking and cycling and discourages car reliance, the streets of Al Salamat are generally risky with their narrow and interrupted sidewalks. The landscape of the neighborhood is quite poor so there are no siting or walking facilities. Additionally, there are no cycling paths and there are generous parking lots that reach to 4 parking lots for each housing unit (Fig. 3).

![Figure 3: Car oriented mobility in Al Salamat and insufficient public transportation nodes.](image)

As ease of mobility requires connection and integration between housing clusters within the neighborhood, housing clusters and neighborhood services, services in each
neighborhood and between the neighborhood and the city. There is some sort of connection and integration with service facilities and with surrounding neighborhoods but only through private cars. Many residents use informal routes by driving in open spaces in order to minimize their trip lengths. This is apparently a result of the inappropriate design and arrangement of the plots clusters.

For public transportation, the ideal design should cater for increasing the accessibility to public transportation nodes and should provide fewer parking spaces. As shown in Figure 3, two bus lines are serving the neighborhood but the locations of the bus stops are not reachable by all. Also, there is no clear bus stop signs or appropriate shading. Bus timings are not shown in many cases. Private car parking are available everywhere.

**Mixed use:** Mixed use encourages local offices/workshops, home-working and multiple use of space. It also helps diversify accessible job opportunities with good local training services. While the original master plan of Al Salamat provides more mixed use opportunities, the actual as built status is less mixed as it lacks many services and working opportunities (Fig. 1).

**Adaptability:** Adaptability is crucial for any design for sustainable urban form where buildings are designed for use change and houses are designed to be easily extended for evolving family circumstances while open spaces should be multi-functional and permit a variety of social activities. Due to its ample area of 45m x 45m, housing plots allowed for the extension of private houses as many residents have embarked on changes that respond to their on-going changing needs. On the other hand, open spaces are mainly deserted with no clear definition or ongoing social activity.

**Local Autonomy:** One essential item for local autonomy is the community participation where locals can be involved in the design and managing/maintaining their local resources such as parks, sport fields, etc. For Al Salamat, there was no participation in the design or the management activities with local authorities and organizations.

**Environmental Quality:** Good environmental quality requires traffic reduction and air quality management, minimizing reliance on cars, encouraging the use of public transportation, car sharing, walkability and redeveloping brown areas. Accordingly, in Al Salamat environmental quality might be adversely affected by the heavy reliance on private cars, inappropriate connectivity and long walking distances to services and facilities, inefficient public transportation system with a few number of bus stops with no proper shades, inappropriate pedestrian sidewalks, and finally the lack of utilization of renewable energy sources.

5 **Analysis of the Urban Form of Shaubat Al Wuttah**

Shaubat Al Wattah community is proclaimed as one of the very few pioneering sustainability-oriented projects in UAE. It is located in the south east side of Al Ain city, 15km away from the city center. It covers a total area of about 460 ha encompassing 1580 single family houses in five housing clusters as shown in Figure 4.

Each housing cluster center contains a small mosque, a kindergarten, shops and a playground area. The project is currently under development.

**Density:** The total targeted population is about 14,000. The housing plot area is 30mX36m much less that the conventional case study, which reflects tendency towards compactness in urban design. The Gross density is about 30.5 person per hectare, which is remarkably higher than the gross density of the conventional case study that is only 11.3 pph. So, from comparative point of view the urban design of this neighborhood is more compact.
and much dense that the conventional one. This is a positive move towards sustainable urban form, even though it might still have gross density rate that is beyond the global acceptable standard of 50 to 60 pph.

Figure 4: Shaubat Al Wuttah Community.

**Accessibility:** There is a clear connection between housing clusters within the neighborhood. Also, the design has achieved good integration between housing clusters within the neighborhood, housing clusters and neighborhood services, services in each neighborhood and between the neighborhood and the city (Fig. 4). The decentralized distribution of services and facilities are accessible for many houses due to the adopted compact pattern of the urban form. Accessibility has been also endorsed through considering wheelchair requirements at traffic intersections. Comparatively, the urban design of this case study has achieved better accessibility measures than the conventional one. Still, the neighborhood urban design does not fully respect standard catchment areas as various services and facilities are away from walking distance.

**Choice:** Actually, there are limited options for services and facilities. So, reliance on the private car is highly expected. Unlike Al Salamat, the design here is providing attractive pedestrian walkways within a safe environment and distributed rest areas among walking paths. This enables choice of modes of travel. Diversity of housing types and sizes has been also considered where 9 design models are available for residents to select from (Fig. 5). Some house models have “stepless” entrances and other accessible features so that handicapped and/or elderly people can select those designs. **Mobility:** The urban design of Shaubat Al Wuttah provides attractive pedestrian walkways within a safe
environment and rest areas carefully distributed among walking paths. This for sure will encourage walkability as an alternative mode of mobility. Cycling paths are provided as another alternative mode of travel. Car parking lots have been minimized to promote the use of public transport. There are planned bus stops but not clearly defined yet. This integrated system of the different modes of travel within neighborhood including pedestrian walkways, cycling paths and bus stops forms a big difference if compared to conventional neighborhood. Still, the question of whether the current population density of mainly Emirati citizens would be sufficient to support a feasible public transportation system is valid. For connection and integration, there is clear connection between clusters within the neighborhood while the connection of these villas to services is weaker. Still, the connections to other neighborhoods are not strong enough.

![Figure 5: Some of the housing models in Shaubat Al Wuttah Community.](image)

**Mixed use:** The neighborhood design does not provide all required services and facilities. Many services and facilities are not within standard catchment area, which inevitably will increase the reliance on private cars. The neighborhood design does not provide offices/workshops and the notion of mixed uses in the neighborhood is not implemented.

**Adaptability:** For adaptability of the single-family houses designs, originally there were only four different villas designs but have been increased to nine in response to expected user needs. Most villa designs have options for some limited future extensions. For open public space, it has been noticed that there are no generous open public spaces that can be adaptive for various purposes if compared with Al Salmat conventional design. The only vacant space in the middle of the development is Hafeet foothill (Fig. 4).

**Local Autonomy:** Another interesting point of comparison between Al Salamat and Shaubat Al Wuttah is involving people in all the villas design stages of Shaubat Al Wuttah where their recommendations have been considered. For one week, Al Ain municipality and Dar consultant firm held meetings with all the prospectus owners to discuss the design of the housing models. The majority of the owners were satisfied with the designs of their villas after undertaking some suggested modifications. On another front, as mentioned above, not all the required services and facilities commonly required for local neighborhood have been provided.

**Environmental Quality:** Environmental quality as in the case of Al Salamat will still suffer, even with a slightly less degree, from the reliance on private cars in travel than other more sustainable modes of mobility. Locations of services within neighborhood encourages resident to use their private cars instead of walking through the attractive and healthy pedestrian walkways. On the other hand, the insufficient services and activities urge residents to use their cars for far trips. There are designed bus stops and stations that might encourage people to use public transportation instead of their own cars. No renewable energy resources have been utilized in the design of the neighborhood and its houses. The community is located near to an industrial area (Cement Factory) but little no effort of mitigating the effect of such hazard is noticed in the design. Some other
measures have been introduced to enhance environmental quality including high-efficiency public street lighting designed to promote energy-efficiency.

6 Learning from the past and present: A futuristic conceptual scenario

The results of the analysis of the two past and present case studies have divulged positive and negative aspects relevant to urban forms with better but still insufficient move towards sustainable urban form in the recent adopted urban form in Shaubat Al Wattah case study (Table 2). This has in turn revealed the potentials for actions that could shape a future path towards sustainable urban form of local urban communities in UAE.

For density the aim should be increasing the gross density rate to be closer to the global gross density standard of 50 to 60 pph. For accessibility the neighborhood urban design should achieve the planning standard catchment areas so that various services and facilities can be accessed by different modes of travel especially by walking and cycling.

Table 2: Evaluation of Sustainable Urban Form Principles of Al Salamat and Shaubat Al Wuttah.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Salamat Evaluation</th>
<th>Shaubat Al Wuttah Evaluation</th>
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<tbody>
<tr>
<td>Density</td>
<td>Weakly Achieved</td>
<td>Partially Achieved</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Weakly Achieved</td>
<td>Strongly Achieved</td>
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<tr>
<td>Choice</td>
<td>Weakly Achieved</td>
<td>Partially Achieved</td>
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<tr>
<td>Mobility</td>
<td>Weakly Achieved</td>
<td>Strongly Achieved</td>
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<tr>
<td>Mixed Use</td>
<td>Weakly Achieved</td>
<td>Weakly Achieved</td>
</tr>
<tr>
<td>Adaptability</td>
<td>Partially Achieved</td>
<td>Weakly Achieved</td>
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<tr>
<td>Local Autonomy</td>
<td>Not Achieved</td>
<td>Partially Achieved</td>
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<tr>
<td>Environmental Quality</td>
<td>Partially Achieved</td>
<td>Partially Achieved</td>
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</table>

Choice can be enforced through providing more options for services and facilities but this need to thought carefully with population density that can support such proposed variety. Mobility has been significantly improved with the introduction of different sustainable modes of travel within neighborhoods but density is a concern for the economic feasibility of public transportation. Therefore, increasing density, besides other regulative measures, might sound crucial if public transportation to function properly. Also, the connections to other neighborhoods should be considered in neighborhood urban design. Adaptability requires more attention on both the buildings and urban spaces levels. Residents should enjoy the ability to genuinely change and or extended the residential spaces inside their homes while urban spaces should be designed to accommodate various changing social and economic activities.

Achieving local autonomy requires besides the providence of all required services and facilities, the involvement of the community members in managing their neighborhood resources including food production. Finally, environmental quality requires more reliance of sustainable modes of travel such as walking, cycling and public transport. To encourage people to walk or cycle sufficient services and amenities should be provided within walkable distances from homes front doors. Utilization of renewable energy resources and energy efficiency measures should be considered if a better environmental quality is to be achieved.

7 Conclusion

The majority of the research work about energy efficiency in mass housing concentrates on the building scale where the urban dimension receives less attention. Sustainable urban form has been selected as a focus for investigation for studying this effect in the United Arab Emirates as one of the countries that have recently adopted a sustainability
agenda in all walks of development including mass housing development. This country has developed some of the sustainability-oriented pioneering public mass housing schemes that witnessed profound transformation from the conventional sprawl urban designs. The analysis of two experiences; one representing the conventional mass housing development urban design and the second representing a sustainability oriented one revealed that the sustainability principles have been more considered but with various degree of achievement. The result of this investigation paves the way for recommending a futuristic urban form development scenario that is envisaged, if adopted, will lead to a more sustainable mass housing built environment in UAE and maybe in other GCC countries which are sharing most of the environmental, social and economic circumstances.

Acknowledgements
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References


BUILDING A ZERO ENERGY HOUSE FOR UAE: TRADITIONAL ARCHITECTURE REVISITED

Tawfiq F. Abu Hantash

1 Department of Architecture, American University of Ras Al-Khaimah, UAE, tawfiq.abuhantash@aurak.ac.ae

Abstract: The aim of this study is to look back, once again, into traditional architecture and learn the lessons of sustainability. It is through studying specific architectural concepts characterizing traditional architecture around the world that we can understand how that architecture sustained and provided appropriate environments for its inhabitants. The sustainability discourse nowadays is mainly concerned with inventing new technologies and materials which could save some of the energy required to operate utilities. Usually it is an additional cost which we initially invest in order to achieve this added value to our buildings. This study will briefly introduce a design approach which is based on achieving sustainability through implementing traditional solutions for the issues of heat, ventilation and natural light. Although those solutions were traditionally embodied in forms that can have significant cultural and social connotations, they are employed here to be tested for their environmental role and to a certain degree their influence on the building envelop as formal elements participating in the making of architectural character. Such elements where extensively used in contemporary Arab Architecture as formalistic stylish elements in order to localize the identity of that architecture. To evaluate the appropriateness of the abovementioned traditional concepts in achieving environmental sustainability within the contemporary circumstances, a Zero Energy House (ZEH) shall be built and tested as an empirical aspect to prove the preposition of this study. The house will be built in the American University of Ras AL-Khaimah (AURAK) campus in collaboration with other colleagues in the School of Engineering. The place is rich with traditional architectural elements such as Courtyards, Wind Catchers and Mashrabiya as part of its architectural heritage. The process of designing and building the ZEH will take 12 to 15 months. Therefore, the data which will result from building and testing the Zero Energy House shall be utilized and highlighted to support of the objective of this study.

Keywords: Sustainability, Traditional Architecture, Zero Energy House, Wind Catchers, Mashrabiya (Double Skin Facades).
1 Introduction

Sustainable buildings are currently emerging as a new building type which is energy efficient, environmentally friendly and architecturally significant. The sustainability of such buildings contributes to the sustainability of the society, the cultural values and most importantly the economy. Moreover, the pertaining technological advancements in the building industry are also expected to be influenced through providing appropriate solutions to attain sustainability measures.

On another level, the design of modern buildings which utilizes light weight new materials to achieve structural feasibility on one hand and providing large glazed openings to allow for more interaction between inside and outside and bring in natural light, has in many ways increased the need for energy to humanize those buildings and enable them to be comfortable for their inhabitants. Accordingly, and considering the rapid growth of population which leads to higher and higher impact on the grid, this forces us to look for passive sources of energy which can compensate the required amounts and to develop a design approach which helps reduce the need for energy and eventually reduce the pressure on the Grid. Such design approach is oriented towards the study and evaluation of some traditional architectural elements which are expected to provide, with some improvements, solutions for the reduction of energy consumption in buildings.

Towards that end, AURAK, which has a proven record in the research and innovation of knowledge pertaining to renewable energy, is intending to build a Zero Energy House (ZEH) taking into consideration the exploration and incorporation of traditional architectural elements in the design and to test their suitability and efficiency in reducing energy consumption inside the house.

In this paper which I consider as a DESIGN RESEARCH study preceding the design and construction of the ZEH and then testing its compatibility with the standards established for this type of buildings. In the First Part of the study, the properties of the courtyard, Wind Catchers and Mashrabiyyah and their role in traditional architecture shall be explored. The potential of using those elements in the ZEH and the suggested improvements in order to cope with the contemporary house design shall also be discussed and evaluated depending on other resources that have already conducted studies on those elements. In the Second Part, reflections on the use of such elements shall be made as well as some recommendations on how those elements can be utilized to achieve the best results in building the Zero Energy House.

2 Vision

This study is aiming to set the theoretical framework and guiding principles for the building of the Zero Energy House in UAE. It is based on utilizing the traditional concepts of the Courtyard, The Wind catcher and the Mashrabiyyah (Double Skin) as means of reducing the heat gain and eventually, the need for energy required to cool the indoor spaces of the house.

Accordingly, it can be considered as the ARCHITECTURAL CONCEPT which sets the design guidelines for building a model house which meets environmental sustainability measures of energy consumption as well as socio-cultural sustainability through identifying the architectural character of the house. Therefore, such passive design measures will be used to minimize the need for active design measures in order to guarantee efficient design and planning of the house to provide comfort for its inhabitants while keeping a net Zero Energy resultant.
3 Traditional Architecture

Traditional architecture is the outcome of how humans read their PLACE (genius Loci). It is how they respond to the place where they live in a smart way. How they utilize resources and knowledge of building in making the built environment and adapt it to their comfort (Fig. 1)

![Sheikh Saeed Al Maktoum house, Dubai](image)

Figure 1: Sheikh Saeed Al Maktoum house, Dubai

Traditional architecture therefore introduces the most appropriate solutions that people developed through the process of trial and error to overcome the climatic conditions of their place. They adapted themselves socially and culturally to such solutions. Therefore, we can say that such harmony between humans, their socio-cultural aspects and the environment has collaborated to make the physical environment embodied in architecture and the different elements that constitute to this architectural identity.

Elements of traditional architecture that play major role in controlling the climatic conditions include: courtyards, building envelop, wind catchers, building materials, size and location of openings, and many other elements. However, for the purpose of this study, I am concentrating on three elements which are the courtyard, the mashrabiyyah and the wind catcher. They are discussed in the following:

3.1 Courtyard:

An outdoor space, piece of nature, created in the middle of the house and surrounded by the rooms of the house. It provides privacy and security for the users and it provides sun and ventilation for the rooms around it. Also the courtyard in the middle of the house enables the houses in a traditional urban neighbourhood to attach to each other representing the strong social solidarity amongst the members of the society, granting them security and safety and most importantly providing them with protection from climatic conditions represented in the strong sun and dusty wind.

From a climatic point of view, courtyards provide shade, ventilation and most importantly, air movement creating a draft of cold air coming downwards to the courtyard at night and hot air moving upwards at day time. (Fig. 2)
With a proper orientation of the courtyard as well as the openings of the rooms surrounding the courtyard, one can say that it will have a positive effect on the temperature inside the house. Also, the provision of arcades in the courtyard will provide more shade on the facades which again, contributes to reducing the heating effect on the walls. (Fig. 3)

Courtyard house as a building type that existed in many regions of hot and humid climates is a passive solar solution. The performance of the courtyard with respect to thermal and ventilation aspects has been tested using Computation Fluid Dynamics (CFD) simulation and proved that a courtyard improves remarkably the thermal performance of the house and eventually reduces the needed energy to cool down the internal spaces (Almhafdy 2014). (Fig. 4)

The use of the courtyard in the design is not limited to traditional houses only. It is used also in modern architecture in different ways. Le Corbusier created a courtyard in the first floor of Villa Savoye and also he created a roof garden (Fig. 5: (a)). Those two elements were used, from the designer's view, to bring nature inside the villa and utilize the sun as
much as possible taking into consideration the cold weather in the place of the villa. Also, he wanted to compensate for the area of the garden which was occupied by the structure of the villa (Fig. 5: (b)). The roof garden was created to complete the natural balance of the place. This contributes to the environmental sustainability of the Villa.

Figure 5: (a) Villa Savoye from top            (b) Villa Savoye courtyard

3.2 Mashrabiya (Double Skin Façade DSF):
Traditionally, Mashrabiya served many purposes (Fig. 7):

1- Reduce the heat coming inside the house,
2- Reduce the glare of the outside sunlight,
3- Provide privacy,
4- Aesthetic expression for the interior as well as for the exterior,
5- Noise control.

Figure 7: Traditional Mashrabiya

Hence, building envelope is the most important factor in keeping the inside environment insulated from the outside. It prevents heat from transferring both ways from outside to inside and vice a versa. (Fig. 8)

Figure 8: Modern Mashrabiya from inside
In traditional buildings, the envelop or the external wall was thick and massive since it was a load bearing wall on one hand, and made of natural materials mostly earth and stone and sometimes wood on the other hand. Therefore, by the virtue of its size and materials, the external wall will provide the required heat insulation by keeping heat from transferring within it.

Another aspect for this traditional external wall (envelop) is the use of small openings. Although structural need could be behind having thick walls with small openings which are usually vertically proportioned, but as a result of that it helped in achieving privacy on one hand and in reducing the chances of heat penetration to the internal spaces on the other hand.

Building technology now a days provided solutions for the structural requirements of buildings so that thick walls are not needed any more. With regards to thermal performance which the traditional wall used to do, we need to treat the building envelop as follows:

1- It reflects sun rays and not absorb it (Color and Texture),
2- It has thermal insulation that prevents heat from reaching inside (Material),
3- It circulates the hot air on the skin of the building by creating air draft between two skins (Double Skin).

![Figure 9: Solar Decathlon 2013](image)

The first and second points are concerned mainly with the selection of insulation materials, texture of the external surfaces and their color. While, the third point is about installing a second skin in front of the original or what is called call the structural envelop of the building to provide the following benefits:

1- Shade resulting from the outer skin on the inner skin and on internal spaces of the building, (Fig. 9)
2- Filtering and improving the quality of natural light and glare coming to the inside of the building, (Fig. 10)
Figure 10: Abu Dhabi Central Market Façade

3- Creating an air draft between the two skins to reduce the effect of heat conduction between air and the inner skin of the building. (Fig. 11)

Figure 11: Double Skin Detail

It has been emphasised in many studies that double skin facades reduce 19%-40% of the energy consumption depending on the materials (Hamza 2005). The air flow between the inner and outer skins provide natural ventilation. Additionally, it provides an architectural opportunities to create transparent facades which are not achievable with the conventional curtain wall or masonry facades.

The application of the Mashrabiyyah or the Double Skin Façade could also be achieved by using traditional materials that are locally produced and traditionally used, namely Al-Arish (Palm Leaves). (Fig. 12)

Figure 12: Arish House
Al-Arish, which is made of the Palm Leafs is available locally and could be developed to serve the purpose of building Double Skin technique provides protection from sun and, beside its function in front of facades, it could be used to build shading pergolas, partitions, screens and even roofs which blend buildings with its local environment and contribute to emphasising its local identity. Additionally, as a local material, it is the best sustainable solution to be used in solving problems of shade, heat and privacy (Piesik 2012). (Fig. 13)

Moreover, another dimension to the use of locally manufactured elements such as Al-Arish would contribute to the survival of local traditional crafts and even push it to new limits. This will definitely enhances the social as well as economic sustainability of the communities which are making their living out of this industry.

### 3.3 Wind Catchers:

Wind Catchers are traditional architectural elements that are used in hot and humid regions like the Gulf, Egypt and Iran. It is a 5-8 meters high tower that is hollow from inside and sits on top of houses to collect air from high points and bring it down to the internal spaces of the house. In most cases in a house it is only one tower over the living or sitting room. In large houses they can be more than one. (Fig. 14)

The main function of this Wind Catcher is to provide natural ventilation for the house and to improve the thermal performance. A testing was conducted on a reduced scale model for a wind catcher in Yazd in Iran by using a Computational Fluid Dynamics CFD software concluded that the Wind Catcher was effective in lowering the temperature by 17% to 26% during the warmest hours of the day (Hedayat 2015). The mass of the tower could also store the night cold air temperature which can be used in the next day (Hedayat 2015).
Some issues with the Wind Catchers need to be developed in order to use it practically. Of such issues is the dust and humidity carried by the wind to the inside of the house directly. Some studies have been conducted to overcome such issues, however, mainly they were at the commercial level and lack the sensitivity in dealing with the traditional form of the Wind Catcher as a cultural icon. One practical proposal which could be tried is to utilize the air collected by the Wind Catchers and feed it as FRESH AIR to HVAC equipment. The reduced temperature of this fresh air by the effect of the Wind Catcher will reduce the pressure on the AC equipment and eventually reduces its energy consumption.

Another aspect of the Wind Catcher that could be utilized is by making it a Solar Chimney. By installing a thermal conductive surface (Metal Plate) in the highest point of the Wind Catcher it will be heated up by the sun and accordingly it will heat the surrounding air. The hot air will ascend in the Wind Catcher and will create a negative pressure which, automatically, drag colder air to move in the house (Fig. 15). If a water feature is installed in the main spaces the house or in a courtyard, air will be cooled while moving towards the Wind Catcher. This feature also improves the thermal comfort and ultimately, reduces the energy consumption on the air conditioning and ventilation of the house.

4 Design of the Zero Energy House

Through the demonstration of traditional elements discussed above, and taking the results of this study as well as others which are referred to here, it looks that utilizing the three elements and even more, can easily reduce the required energy in this house. And since the basic methodology for this study is to follow a Design Research approach, thus, each of the abovementioned elements including other elements to be included in the project shall be subjected to thorough investigation and evaluation in order to guarantee the best performance with regards to the reduction of energy consumption. The design, on the other hand, shall not compromise the aesthetic and functional values associated to the culture and to the place.

The main aspects that the ZEH shall take into consideration are grouped in the following:
- Design: decisions shall concentrate on Building orientation, floor layouts (courtyards), building mass, use of shading elements (mashrabiyyah), traditional wind catchers and solar chimneys, size of openings, Landscaping.
- Building technology: Thermal insulation in roof and walls, building details, building tightness (doors and windows), roof gardens, environmental friendly materials (Arish).
- Renewable energy sources: Use of PV panels to generate needed power. The use of solar energy shall be the main source of renewable energy that will be used in the building of this house.
After building the ZEH, it will be tested against the many issues of sustainability especially those related to comfort of the internal environment such as temperature and ventilation.

5 Conclusion
The increasing demand on energy to meet the needs of modern houses will reach to a point where renewable energy sources alone are not sufficient. The design of the house should be sensitively done in a way that takes into consideration reducing the amounts of required energy through passive solutions. Courtyards, Wind Catchers and Double Skin Facades as well as the use of local materials such as Arish are not the only means by which we can bring down the energy consumption down. Orientation of the building, location and type of windows, tightness of the building, and method of insulation of the external envelop and the quality and source of the materials used in construction are also important factors that contribute to the reduction of energy consumption.

The matter will be much more feasible if we use efficient equipment which consumes less energy such as Inverter AC compressors, LED lighting and green products that increases the level of sustainability and reflects positively on other aspects such as socio-cultural sustainability and economic sustainability.

With regards to the Zero Energy House which will be built on the premises of this study, the architectural concept shall reinterpret the traditional elements studied here by utilizing their properties in a contemporary way while keeping its authentic meaning and function.

Other aspects of the house shall take into considerations the state of the art technological advancements in the fields of renewable energy pertaining to solar power. A team of specialized faculty members and researchers at AURAK will work in parallel to equip the house with the most feasible PV systems and power storage devices which can generate and store the sufficient energy needed for the house.

References


Abstract: The need to connect with nature is a basic human one, similar to the need for fresh air, clean water and healthy food. This innate affinity has been defined as Biophilia. It has been recognized that being able to see nature or its natural indoor substitutions or just being in nature like spaces can reduce stress, improve creativity and productivity as well as increase the possibility of healing faster. Therefore, connection to nature for building occupants is being increasingly acknowledged as a critical component in the occupant's health, well-being and overall satisfaction. The quest for an exact identification of the components that affect human satisfaction, health and well-being within the built environment has driven extensive research. Access to daylight, view out and nature emerge as the most influential factors. Hence, natural light, vegetation and fresh air are the most studied aspects of biophilic design through psychological theories and applied sciences. The aim of this paper is to explore the status of knowledge on the multidimensional biophilia factors and unveil their effect on human health and well-being in different built environment scenarios. The paper also discusses the various ways to provide people with their daily connection with nature to ensure a sustainable community. The most dominant finding from the literature review is that; no matter how much the world population continues to urbanize, people will always tend to prefer being connected to nature and natural like elements on urban spaces. Another important finding is the multiplicity of options, other than direct access to daylight, air and greenery, to incorporate nature compensation into the built environment such as; space and place orientation that elicit sense of refuge, mystery and prospect, the flow of water bodies and the reflection on its surface, as well as details, fabric and form of indoor elements.

Keywords: Biophilia, nature, health, well-being, Building typology, literature review
1 Introduction

Until the recent past, the human world had been an undivided part of the natural world, but the developed world that humans live and evolve in now are totally different (Cronon 1996, Nebbe 2006, Pergams et al 2008). Thus most of us have been physically and psychologically disconnected from nature ever since our number in urban environments has been in a continuous increase while the natural environment is in continuous decrease (von Lindern et al 2013, Capaldi et al 2015). Nature impacts the urban life in different ways; it can provide a cleaner environment, healthier and more sociable community and therefore a better economic status for the cities. According to Kellert (2005) having an access to open spaces or even to a limited amount of grass and trees can enhance coping and adaptive behaviour as well as can result in less health and sociable problems (Kellert 2005, von Lindern et al 2013, Zelenski et al 2015).

The aim of this paper is to first, uncover biophilia’s impact on occupants health and wellbeing in different building environments. Second, it looks into the many different ways nature can be integrated in buildings to contribute to the occupants’ wellbeing in daily life.

2 Biophilia; Definition and Hypothesis

Wilson first defined Biophilia as the “innate tendency to focus on life and life-like processes” (Wilson 1984, Joye 2011, Chang et al 2016), in which it encompasses our physical, emotional, and intellectual need for a connection with nature and life like processes. Ulrich interprets this idea that our genes play a partial role for having positive responses to natural elements and such reposes had adaptive significance during evolution (Ulrich 1993, Beery 2015). Some researchers defined biophilia as the study of the human response to the natural environment and the relationship between humans and natural systems, which is, in its simplest form, “a sense of place” (Williams 1996, Haywood 2014). It was proved by researchers that it is an important deep-seated need for the human development to affiliate with the diversity of nature (Roetman et al 2008, Nisbet et al 2008, Joye et al 2011, Newman 2014, Söderlund 2015) and this affiliation is based on emotions and human evolution (Kellert et al 2015). Kellert suggested that biophilia is likely to increase mental wellbeing and personal fulfilment as well as being considered to be a basis for the human conservation of nature (Kellert 2003, Zelenski et al 2015, McMahan 2015).

According to Wilson our affinity for natural environments originates from a biological bond deeply rooted between humans and the natural world (Wilson 1984, Chang 2015, Amiot et al 2015). “In short, the brain evolved in a biocentric world, not a machine-regulated world” (Kellert et al 1995, Amiot et al 2015, Ulmer 2016). Additionally, biophilia is considered a set of complex learning rules that have been ingrained in our genetic history and that the need to relate to natural processes is biological and is essential to our physical and mental well-being (Kellert 1993, Haywood 2014, Beery et al 2015).

Heerwagen and Orians (1995), they hypothesized that there are specific elements, such as habitability cues, resource availability, shelter and predator protection, hazard cues, way finding and movement, that evoke the historical lives of our ancestors in African Savannah. This is why most of the times we tend to replicate the Savannahs when designing landscape (Heerwagen et al 1995, Frumkin 2001). The main features of the savannahs that played role in the survival and well-being of our ancestors are (Orians et al 1992, Joye 2007):

Open grasslands with open vistas that made movements easier
Habitability cues and wide diversity of plant and wildlife that provided food
Predator protection by hills and vistas that provided easy surveillance of weather, animals and hazards. Resource availability and shallow bodies of water that provided food, water and bathing. Clusters of trees with low trunks and large canopies that allowed for climbing and sheltering.

Big sky with a wide, bright field of view to aid visual access in all directions. The main needs of the occupants from their surroundings are: to be inspired, invigorated, comforted and reassured, they also want spaces that make them more productive and healthy that creates delight when entered, pleasure when occupied, and regret when departed. Table 1 describes nine hypothesized fundamental aspects of the human biological basis for valuing and affiliating with the natural world (Kellert 1993).

Table 1: adapted from The Biophilia Hypothesis (Kellert 1993)

<table>
<thead>
<tr>
<th>Value</th>
<th>Definition</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetic</td>
<td>An emotional response to the physical beauty and attraction of nature</td>
<td>Inspiration, harmony, peace and security</td>
</tr>
<tr>
<td>Dominionistic</td>
<td>The tendency to control and manipulate nature</td>
<td>Mechanical skills, physical power</td>
</tr>
<tr>
<td>Humanistic</td>
<td>An emotional response to care for and become attached to nature</td>
<td>Bonding, sharing and companionship</td>
</tr>
<tr>
<td>Moralistic</td>
<td>Moral and spiritual connection to nature. Emphasizes right and wrong behavior toward the natural environment</td>
<td>Order and ethics</td>
</tr>
<tr>
<td>Naturalistic</td>
<td>The satisfaction we obtain from direct experience with nature</td>
<td>Curiosity, outdoor ability, physical well-being</td>
</tr>
<tr>
<td>Negativistic</td>
<td>The fear and dislikes we have with nature</td>
<td>Security, safety and protection</td>
</tr>
<tr>
<td>Scientific</td>
<td>The study of biological processes and observation of nature</td>
<td>The imperative want to obtain knowledge, observation</td>
</tr>
<tr>
<td>Symbolic</td>
<td>The tendency for humans to use nature to communicate thoughts metaphorically</td>
<td>Communication, psychological development</td>
</tr>
<tr>
<td>Utilitarian</td>
<td>The material gain that humans benefit from the exploitation of nature, either for desire or need</td>
<td>Physical sustenance and security</td>
</tr>
</tbody>
</table>

3 Benefits of Biophilia

The Biophilia hypothesis proposes that, humans have an innate connection with the natural world and that exposure to the natural world is therefore important for their wellbeing (Kellert et al 1993; 1995, Joye et al 2011). The concept of biophilia coupled with harnessing the connection to nature covers a range of benefits relating to psychological well-being, stress reduction, cognitive functioning, productivity, human development, social behavior (Heerwagen et al 2001, Thatcher 2012, Thatcher 2014), and human conditions such as intellectual capacity, emotional bonding, aesthetic attraction, creativity and imagination (Kellert 2008, Mayer et al 2008). There is a growing body of research on the connection between human health, well-being and behavior with nature. These tests range from studies of kids in nurseries to elderly people in public housing projects (Heerwagen et al 2001, Balmford et al 2005) using varied methods such as views from windows, having indoor vegetation or interacting with nature while strolling, and even substitutes such as pictures and videos of natural elements. (Velarde et al 2007).

Biophilia has many benefits on the occupant, and the last 25 years marked the interest of researchers in connecting occupant’s health with the built environment (Velarde et al 2007). Table 2 summarizes the benefits of interacting with nature (Keniger et al 2013). This paper focuses on three main health responses to biophilia when individuals interact...
with their environment; psychological health, cognitive functioning and physiological health.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Psychological well</td>
<td>Positive effect on mental processes</td>
<td>Increased self esteem, Improved mood, Reduced anger/frustration,</td>
</tr>
<tr>
<td>being</td>
<td></td>
<td>Psychological well being, Reduced anxiety, Improved behavior</td>
</tr>
<tr>
<td>Cognitive</td>
<td>Positive effect on cognitive ability or function</td>
<td>Attentional restoration, Reduced mental fatigue, Improved academic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>performance, Education learning opportunities, Improved ability to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>perform tasks, Improved cognitive function in children, Improved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>productivity</td>
</tr>
<tr>
<td>Physiological</td>
<td>Positive effect on physical function and/or</td>
<td>Stress reduction, Reduced blood pressure, Reduced cortisol levels,</td>
</tr>
<tr>
<td></td>
<td>physical health</td>
<td>Reduced headaches, Reduced mortality rates from circulatory disease,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Faster healing, Addiction recovery, Perceived health/well-being, Reduced</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cardiovascular, respiratory disease and long term illness, Reduced</td>
</tr>
<tr>
<td></td>
<td></td>
<td>occurrence of illness</td>
</tr>
<tr>
<td>Social</td>
<td>Positive social effect at an individual</td>
<td>Facilitated social interaction, Enables social empowerment, Reduced</td>
</tr>
<tr>
<td></td>
<td>community or national scale</td>
<td>crime rates, Reduced violence, Enables interracial interaction, Social</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cohesion, Social support</td>
</tr>
<tr>
<td>Spiritual</td>
<td>Positive effect on individual religion</td>
<td>Increased inspiration, Increased spiritual well-being</td>
</tr>
<tr>
<td></td>
<td>pursuits or spiritual well being</td>
<td></td>
</tr>
<tr>
<td>Tangible</td>
<td>Material goods that an individual can accrue for</td>
<td>Food supply, Money</td>
</tr>
<tr>
<td></td>
<td>wealth or possession</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Psychological Benefits

One of the psychological impact of access to nature is based on the fact that natural environment emit cues and sensory patterns that our brain responds to functionally (Kellert et al 2011, Tidball 2012). Hence passive viewing through windows, or looking at videos and photographs of nature helps in reducing stress levels, improves mood and promotes healthy lifestyle (Ulrich 1993, Kellert2005, Velarde et al 2007).

The Stress Recovery Theory predicts that illness and stress recovery as well as the usage of pain killers can be affected by being connected to natural elements, on the other hand the built environment settings can prevent this recovery (Ulrich 1984, 1999). When people are confined to limited mobility environment (prison or in a work environment) and suffer from high stress levels it is very sufficient to have a direct, indirect or even symbolic contact with nature (Ulrich 2003).
Other studies proved that strolling in a natural environment can help improving the mood (Mayer et al 2008) and promote a positive overall emotional state even for the occupants that suffer from mood disorder (Berman et al 2012).

Another psychological benefit is that from ages ago it was believed that viewing nature elements such as vegetation and water helps in the patient’s recovery process, that’s why one of the main elements of designing the first hospitals in Europe was an attached close garden for the patients (Ulrich 2002). Being connected to nature either directly, through vegetation and light, or symbolically through pictures and videos, was found to improve healing and recovery from illness and major surgical procedures (Kellen, 2005)

3.2 Cognitive functioning

Researchers have found strong link between being connected to nature and occupants cognitive functioning and tasks that requires memory and concentration, these findings provides proofs for links between nature in the built environment and children growth as well as work performance (Wells 2000, Kellert 2005, Bratman et al 2012).

It’s highly recommended for children growth and mind development to allow them access to natural play grounds in schools, day care centres and other educational centres or even at home (Wells 2000, Kellert 2005). Children’s need to explore nature and living organisms helps in their cognitive functioning, social and emotional development (Kahn and Kellert 2002, O’Brien 2009), as well as language learning (Arreguin-Anderson 2015). Natural platforms and objects provide different aspects to different ages of children. For older ones it helps them to find their way, have group decisions, being able to respond to changeable contexts and improve problem solving abilities. On the other hand for younger children groups, nature encourages them to explore and imagine (Heerwagen 2009, Derr 2012).

On the other hand, Attention Restoration Theory is a contemporary theory developed by Rachel and Stephen Kaplan (Kaplan et al 1989, Ohly et al 2016), that describes how environments with nature effect the mental fatigue in settings with therapeutically functional elements that plays role in providing rest, isolation and contemplation in order to allow attention recovery (Heerwagen et al 2001, Ohly et al 2016).

Group of researchers found that views through windows and taking a walk in along a natural walkway can increase the ability to concentrate (Heerwagen et al 2001, Harting et al 2003) and that the quality of the occupant’s life can be affected by attention fatigue (Kaplan 2004, Bratman et al 2015).

Add to that, Productivity Studies within the working environment has been proved to be affected by the connection to natural environments either directly or indirectly (Kellert 2005, Beatly 2009, Gray et al 2014). Offices that consists of natural views through windows allows the workers to feel less frustrated, more relaxed and felt satisfied (Kaplan 1993, Farley et al 2001, Aries et al 2010).

3.3 Physiological

Stress, depression, anxiety and over exertion can cause number of physiological processes for example hormones secretion, neurons degeneration in the brain and immune function suppression. Some hormones can affect our sleep and relaxation by effecting our digestion, blood pressure, pulse, and breathing (Townsend et al 2010, Dias 2015, Hagerhall et al 2015).

Exposure to daylight can readjust the cortisol and melatonin levels that can increase under stress (Townsend et al, 2010, Berto et al 2015). Add to that having the accessibility to
green spaces encourage physical activities which can in return reduce stress hormone levels (Grahn and Stigsdotter 2003).

Researches on older adults proved that walking for them has several benefits on their mental health and well-being (Sugiyama and Thompson 2008) to mention some; improving cognitive functioning (Yaffe et al 2001) that can minimize Alzheimer’s and dementia severity (Townsend et al 2010, Cevizci et al 2013), reducing depression (Mobily et al 1996), developing healthy muscles and bone that can reduce the “falling “risks (Townsend et al 2010, Chang et al 2016).

4 Biophilic Design

Biophilic design is: “the design philosophy based on theories; such as: biophilia hypothesis (Wilson, 1993; 1984), Biophobia hypothesis (Ulrich 1993) the savanna hypothesis (Orians et al 1992), the habitat theory and prospect-refuge theory (Appleton, 1975), and the preference matrix (Kaplan et al 1989); and supported by data from psychological and health research that encourages the use of natural systems and processes in the design of the built environment” (Kellert et al 2011, Russell et al 2013, Ryan et al 2014, Kellert et al 2015). Biophilic design may increase the likeability of nature by more exposure to natural processes and elements in a controlled environment through incorporating natural features and systems into the built environment in order to allow human beings to be exposed to the much needed nature. However just like any design strategy, biophilic design strategies must be implemented with the building occupants, location and function in mind. (Kellert 2008, Kellert and Finnegan 2011, Kellert 2012, Browning et al 2014, Gillis et al 2015).

Heerwagen suggested that buildings should be designed based on survival needs and wellbeing. Designs should be built around our primitive preferences and our connection to nature. Occupants of built environment wants from their surroundings to be inspiring, comforting, reassuring, delightful, as well as makes them invigorated, healthy, pleasurable when occupied and regretful when departed. (Heerwagen et al 2008).

According to Heerwagen (2003) Bio-inspired design basis consists of general characteristics of living organisms and life like processes that are (Heerwagen 2003):
Movement: Movement is characteristic of all living organisms as well as life supporting systems, such as: the sun, clouds, fire, and water Growth and development: Living organisms exhibit patterns of development due to the reproductive processes, that unfold over time from some simpler form to a more complex one Complexity. All living organisms and life-like processes display some kind of complex design that, sometimes, is not apparent at first glance, but which is discovered through sensory exploration Fractal patterning. Processes of fractal growth and involving events determine the forms and patterns of living organisms, systems, and natural processes Organic shapes. Nature is not rectilinear. The shapes of natural objects are determined by their fractal growth pattern, limitations imposed by the conditions of life on earth, especially sunlight and gravity.

Multi-sensory. Living organisms are sensory rich and convey information to all human sensory systems, including sight, sound, touch, taste, and odor. Abstract informational characters: this consists of the environmental qualities that have the highest psychological appeal when visualized and are the fundamentals to process information. coherence and legibility are the two qualities that aid environmental understanding, while complexity and mystery aid exploration.
It’s not necessary to have large expansive landscape fields in urban settings in order to provide the occupants needs. Indoor plants, sitting areas in the outdoor with trees and following themes of nature, can be beneficial as well (Heerwagen et al 2001). There are three main types of connecting with nature that were identified by Kellert and Calabrese as shown in table 3, either by direct and immediate experience, or by human interventions, or even by symbolic contact (Kellert et al 2015).

<table>
<thead>
<tr>
<th>Direct experience of nature</th>
<th>Indirect experience of nature</th>
<th>Experience of space and place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Images of nature</td>
<td>Prospect and refuge</td>
</tr>
<tr>
<td>Air</td>
<td>Natural materials</td>
<td>Organized complexity</td>
</tr>
<tr>
<td>Water</td>
<td>Natural colors</td>
<td>Integration of parts to wholes</td>
</tr>
<tr>
<td>Plants</td>
<td>Simulating natural light and air</td>
<td>Transitional spaces</td>
</tr>
<tr>
<td>Animals</td>
<td>Naturalistic shapes and forms</td>
<td>Mobility and way finding</td>
</tr>
<tr>
<td>Weather</td>
<td>Evoking nature</td>
<td>Cultural and ecological attachment to place</td>
</tr>
<tr>
<td>Natural landscapes and ecosystems</td>
<td>Information richness</td>
<td>-</td>
</tr>
<tr>
<td>Fire</td>
<td>Age, change and patina of time</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>Natural geometries</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>Biomimicry</td>
<td>-</td>
</tr>
</tbody>
</table>

4.1 Biophilic Building characteristics:

To be able to understand what are the elements of nature that attract or repels the occupants, is the core of bio-inspired design. Heerwage and Hase suggests that “design should be built around primitive preferences” and the need to connect to nature, they came up with a table 4 of Biophilic Building Characteristics that explains each key dimension that should be targeted (Heerwagen and Hase 2001). However, when trying to integrate nature or any of its elements into the building design to enhance the occupant’s health and well-being many issues will emerge, such as (Lyubomirsky et al 2013, Capaldi et al 2015):

What’s the best type of nature for the specific environment? And in what dose?
How long the effects would last?
What would an optimum result require?

<table>
<thead>
<tr>
<th>Key dimensions</th>
<th>Attributes and qualities</th>
</tr>
</thead>
</table>
| Prospect (ability to see into the distance) | • Brightness in the field of view (windows, bright walls)  
• Visual distance  
• Horizon/sky imagery (sun, mountains, clouds)  
• Strategic, viewing locations  
• View corridors |
| Refuge (sense of enclosure or shelter) | • Canopy effect, lowered ceilings, screening, branch like forms over head  
• Variations in light levels (darkness suggests refuge)  
• Enclosing surfaces |
| Water (indoors or views) | • Glimmering or reflective surfaces  
• Moving water  
• Symbolic forms of water |
| Biodiversity | • Varied vegetation indoors and out (trees, plants, flowers)  
• Windows positioned to frame views of nature  
• Nearby outdoor areas with vegetation and animals |
| Sensory variability | • Changes that affect the senses  
• Color, textures, temperature, air movement, natural light variation |
| Biomimicry | • Design derived from nature  
• Natural forms, patterns and textures  
• Fractal characteristics |
**4.2 Patterns of Biophilic Design**

Through an extensive interdisciplinary research, a large number of researchers developed useful patterns for designers of the built environment integrating Biophilic Design in buildings. Fourteen (14) main patterns were characterized in 3 main categories branded: nature in the space, nature of the space and natural analogues (Browning et al 2014) and are summarized next. These patterns can be implemented flexibly and adaptively to both interior and exterior environment.

### 4.2.1 Nature in the Space Patterns

This category focuses on the actual physical presence of nature like plants, water, animals, breezes, sounds, scents and other similar natural elements in the space. In order for these patterns to achieve their full potential, a meaningful and direct connection to these natural elements through diversity and multi-sensory interactions is required. Nature in the Space encompasses seven biophilic design patterns:

- **Visual Connection with Nature.** A view to elements of nature, living systems and natural processes.
- **Non-Visual Connection with Nature.** Auditory, haptic, olfactory, or gustatory stimuli that engender a deliberate and positive reference to nature, living systems or natural processes.
- **Non-Rhythmic Sensory Stimuli.** Stochastic and ephemeral connections with nature that may be analyzed statistically but may not be predicted precisely.
- **Thermal & Airflow Variability.** Subtle changes in air temperature, relative humidity, airflow across the skin, and surface temperatures that mimic natural environments.
- **Presence of Water.** A condition that enhances the experience of a place through seeing, hearing or touching water.
- **Dynamic & Diffuse Light.** Leverages varying intensities of light and shadow that change over time to create conditions that occur in nature.
- **Connection with Natural Systems.** Awareness of natural processes, especially seasonal and temporal changes

### 4.2.2 Natural Analogues Patterns

This category focuses on the organic, non-living and indirect evocations of nature. In order for this pattern category to achieve its full potential; rich information in an evolving manner must be provided. Natural Analogues encompasses three patterns of biophilic design:

- **Biomorphic Forms & Patterns.** Symbolic references to contoured, patterned, textured or numerical arrangements that persist in nature.
- **Material Connection with Nature.** Materials and elements from nature that, through minimal processing, reflect the local ecology or geology and create a distinct sense of place.
- **Complexity & Order.** Rich sensory information that adheres to a spatial hierarchy similar to those encountered in nature.

### 4.2.3 Nature of the Space Patterns

This category focuses on the spatial settings in nature, and could be achieved best by engaging spatial configurations with patterns from Nature in the Space and Natural Analogues. Nature of the Space patterns is:
Prospect. An unimpeded view over a distance, for surveillance and planning.

Refuge. A place for withdrawal from environmental conditions or the main flow of activity, in which the individual is protected from behind and overhead.

Mystery. The promise of more information, achieved through partially obscured views or other sensory devices that entice the individual to travel deeper into the space.

Risk/Peril. An identifiable threat coupled with a reliable safeguard.

### 4.3 Design implementations

Table 5 synthesises the benefits on occupant’s health and well-being derived from nature in different building types. Optimised implementation patterns are identified for different building types. The main settings considered include Healthcare facilities, Educational Centres, Offices and Housing.

#### Table 5: biophilic design patterns integration into different building typologies

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Pattern</th>
<th>Pattern integration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Health Care</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower blood pressure, heart rate (Brown et al 2013)</td>
<td>Visual connection with nature</td>
<td>- green wall, - artwork and video with nature scenes, - digital simulations of nature sounds</td>
</tr>
<tr>
<td>Reduced systolic blood pressure and stress hormones (Ulrich et al 1991)</td>
<td>Non visual connection with nature</td>
<td>- highly designed landscape with vegetation (herbs, flowers, plant selection), songbirds, Body of water, insects, soil and earth - natural ventilation - textured materials, warm/cool surfaces, wallpaper and carpet design, material texture and contour - facade and window hierarchy, building skyline</td>
</tr>
<tr>
<td>Positively impacted on heart rate, systolic blood pressure and sympathetic nervous system activity (Li 2010)</td>
<td>Non-Rhythmic Sensory Stimuli</td>
<td></td>
</tr>
<tr>
<td>Enhanced positive health responses; Shifted perception of environment (Kellert et al 2011)</td>
<td>Connection with Natural Systems</td>
<td></td>
</tr>
<tr>
<td>Positively impacted perceptual and physiological stress responses (Baldwin et al 2011)</td>
<td>complexity and order</td>
<td></td>
</tr>
<tr>
<td><strong>Educational Centres</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve mental engagement attentiveness (Biederman 2006)</td>
<td>Visual connection with nature</td>
<td>- Solar heat gain, shadow and shade, radiant surface materials, - HVAC delivery strategy, systems control - space and place orientation, - vegetation with seasonal densification, - window glazing and treatment, window operability and cross ventilation, - water wall, fountain, reflections of water, images with water features - accent details, interior surfaces, natural colour pallet, wall construction, structural systems, facade material, furniture form, - several sides covered reading nooks, spaces reserved for reading and complex cognitive tasks</td>
</tr>
<tr>
<td>Positively impacted on cognitive performance (Mehta et al 2012)</td>
<td>Non-Visual Connection with Nature</td>
<td></td>
</tr>
<tr>
<td>Positively impacted concentration (Kaplan et al 1989)</td>
<td>Thermal &amp; Airflow Variability</td>
<td></td>
</tr>
<tr>
<td>Improve concentration and memory restoration (Biederman et al 2006)</td>
<td>Presence of Water</td>
<td></td>
</tr>
<tr>
<td>Improved concentration, attention and perception of safety (Ulrich)</td>
<td>Refuge</td>
<td></td>
</tr>
<tr>
<td>Benefit</td>
<td>Pattern</td>
<td>Visual connection with nature</td>
</tr>
<tr>
<td>---------</td>
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<td>------------------------------</td>
</tr>
<tr>
<td>Improve mental engagement attentiveness (Biederman et al 2006)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceived improvements in mental health and tranquility (Ryan et al 2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positively impacted on cognitive performance (Mehta et al 2012)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positively impact comfort, well-being and productivity, (Heerwagen 2006)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positively impact comfort, well-being and productivity, (Tsunetugu et al 2010). Improved creative performance (Lichtenfeld et al 2012)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Non-Visual Connection with Nature

- Body of water,
- Artwork and video with nature scenes, digital simulations of nature sounds
- Highly designed landscape, herbs and flowers, songbirds, vegetation, insect, soil, earth, vegetation with seasonal densification
- Green wall,
- Natural ventilation, HVAC delivery strategy, systems control
- Textured materials, warm/cool surfaces, radiant surface materials, wall paint style or texture, transparent materials
- Solar heat gain, shadow and shade,
- Space and place orientation,
- Window glazing and treatment, window operability and cross ventilation, window detail
- Free standing sculptures,
- Building form, structural systems, furniture form, pathway and hallway, partition heights, balconies, staircase landings, open floor plan, elevated planes,
- Views including shade trees and bodies of water or evidence of human habitation,
- Near or complete concealment in meeting rooms and private offices,
- Improved concentration, attention and perception of safety (Grahn et al 2010), reduce boredom, irritation, fatigue (Heerwagen et al 2004)
- Presence of water
- Refuge
- Material connection with nature

### Housing

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Pattern</th>
<th>Visual connection with nature</th>
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<tr>
<td>Improve mental engagement attentiveness (Biederman et al 2006)</td>
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<td>Positively impacted attitude and overall happiness (Rands et al 2010)</td>
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<td>Positively impacted on cognitive performance (Mehta et al 2012)</td>
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<td>Perceived improvements in mental health and tranquility (Ryan et al 2014)</td>
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<td>Positively Impact comfort, well-being and productivity, (Heerwagen 2006)</td>
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<td>Non-Visual Connection with Nature</td>
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<td>Thermal and airflow variability</td>
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</tbody>
</table>
positively impacted concentration (Kaplan et al 1989)

| Improved comfort (Tsunetsugu et al 2010) | Material Connection with Nature |
| Improved concentration, attention and perception of safety (Grahn et al 2010) | Refuge |
| Positively impacted perceptual and physiological stress responses (Taylor 2006) | Complexity and order |
| reduce stress (Grahm et al 2010), reduce boredom, irritation, fatigue (Heerwagen et al 2004) | prospect |
| Reduced stress, increased feelings of tranquility, lower heart rate and blood pressure, Improved concentration and memory restoration and observed preferences and positive emotional responses (Biederman et al 2006) | Presence of water |
| Positively impacted circadian system functioning (Beckett et al 2009) | Dynamic & Diffuse Light |
| Enhanced positive health responses; Shifted perception of environment (Kellert et al 2011) | Connection with Natural Systems |

- space and place orientation, HVAC delivery strategy, systems control,
- window glazing and treatment, window operability and cross ventilation, window hierarchy,
- daylight from multiple angles, direct sunlight, seasonal light, star light, Illuminance, light distribution, daylight preserving treatments, ambient diffuse lighting, task lighting, accent lighting, circadian color reference, color tuning lighting,
- accent details, interior surfaces, natural color pallet,
- wall construction, structural systems, facade material,
- exposed structure, facade and building skyline, floor plan, partition heights, open floor plan, elevated planes
- balconies, staircase landings,
- views including shade trees and bodies of water or evidence of human habitation,
- small protection, several sides covered, near or complete concealment,
- spaces with climate protection,
- reserved spaces for specific activities,

5 Conclusion
This paper aimed first to identify the health and well-being benefits of connection to nature, and then attempts to connect the design patterns implementations in different building typologies. One of the main fundamentals to establish a sustainable flourished community that respect and care for nature is to allow all its occupants a daily connection to natural forms despite their differences in gender, color, financial status or age. The reviewed literature stresses the prominent role that nature plays in not only our health and well-being but also our social and economic life. It is now largely accepted that biophilic design is not a trend that will fade after a while.

The importance of connection to nature being established, the critical recurring question is the reasons behind the neglect of nature which may be linked to lack of knowledge on its positive contribution. In order for the Biophilic Design to reach its highest potential, we must look into how “Biophilia” can move from theory to reality. This could be done through, for example, developing project requirements, design guidelines and performance metrics. Additional considerations include looking into and developing incentives that promotes Biophilia.
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Collaborative knowledge work environments. Building research & information, 32(6), 510-528.


PREFABRICATION IN THE UK HOUSING CONSTRUCTION INDUSTRY

Sohail Alonso-Zandari¹ & Arman Hashemi²

¹,² School of Environment and Technology, University of Brighton, UK.
¹ s.alonso-zandari1@uni.brighton.ac.uk ; ² a.hashemi@brighton.ac.uk

Abstract: This paper aims to explore how prefabricated methods of construction could address housing shortages in the UK. The available literature is reviewed to evaluate current conditions of housing as well as prefabricated methods of construction in the UK. Advantages and limitations of prefabrication are investigated and discussed in relation to the current conditions. Interviews are also conducted as well as case studies in order to understand the challenges and to provide first hand information on current industry practices in the UK housing construction industry. Findings indicate that although offsite construction is widely known and acknowledged, there is little encouragement and incentives to maximise the use of prefabrication in the UK. Extra costs, larger lead time and engineering issues are found to be the key factors preventing the innovative processes of prefabricated construction in the UK's residential sector.

Keywords: Prefabrication, Dwellings, Offsite Construction, Challenges
1 Introduction
The current challenges facing the housing industry are creating an indisputable pressure to innovate and change the way in which house builders are constructing and operating (Tam et al 2007). With an increasing population, one challenge the UK construction industry is facing is trying to meet the rising demands in dwellings (Cheshire & Sheppard 1998). Not only is demand for housing increasing, but it is having a detrimental effect on the price of properties with many observers claiming that we are in the midst of an ‘affordable housing crisis’ (Feldman 2002).

Alongside an increasing population that is resulting in a high housing demand, the UK construction industry is currently facing a shortage of skilled labour (Dainty et al 2005). The industry’s continued growth in output, coupled with its unpopularity as a career choice has put extreme pressure on its labour market capacity (Dainty et al 2005).

One other challenge the UK construction industry is facing is the increasing pressure to become more environmentally friendly. This issue is being further magnified due to the waste generation traditional construction methods create (Jallion et al 2009).

This pernicious state of flux is being experienced nationwide and the need to resolve the challenges that the UK housing industry is experiencing has prompted the interest of academics and professionals to research into potential solutions.

Prefabrication, commonly known as modular construction, offsite construction and modern methods of construction (MMC), is an act of manufacturing a structure or a component in a factory under controlled conditions (Azman et al 2012). The completed feature, which would have normally been built onsite, is then transported to the required location (Ross et al 2006).

Post war building had been identified early on by the British government as challenging (Phillipson 2001) and the shortage of housing after World War II was emphasised once military personnel returned home (Bosch & Philips 2003). Various techniques had been explored to find a main alternative to bricklaying (Phillipson 2001) which led to the phenomenon that was known as the Modern Movement. The Modern Movement raised the argument that mass production was needed in order to cope with the massive social demand (Hashemi 2013).

The 1960’s had been the decade where high rise buildings were being constructed with a heavy reliance on prefabrication (Finnimore 1989). The nature of prefabricated components, in being similar, created friction and disagreements within society (Hashemi 2013). In addition to the aesthetic monotonous controversy, a gas explosion at the infamous Ronan Point, a high-rise building that used extensive precast panels, caused the 18th floor of a 22-story building to collapse (Molkov 1999; Lovell & Smith 2010; Knaack et al 2012). Despite the cause of the explosion not being directly related to the utilisation of prefabrication (prefab), the image of offsite construction had been substantially damaged which ended its accelerated use (Hashemi 2013).

Arguably, the use of prefabrication offers several key advantages over traditional construction techniques. Due to the nature of prefabrication where time savings (Wong et al 2003), increased cost predictability and value for money is enhanced (Hashemi 2013), supporters are of the opinion that the deficit of housing may be met by offsite construction (Steinberg 2007).
It is also thought that prefabrication can reach sustainable targets due to factories being able to control energy and emissions more easily than construction sites (Gibb 2009) as well as managing sustainability targets due to a reduction in construction waste produced (Poon 2007; Tam et al 2007; Jaillon et al 2009; Lu & Yuan 2013). Moreover, as a by-product of utilising offsite construction, it is widely thought that a reduction in labour pressure may be obtained due to requiring less to achieve similar on-site results (Jaillon et al 2009).

Piroozfar et al. (2009) conducted a study where two similar buildings were compared in terms of performance and age, where one had been constructed using a modular-based system and the other building utilised established methods of construction. Under similar uses, it was found that energy consumption of the building that utilised prefabricated elements was 13% better than the benchmark for the good practice, whereas the energy consumption of the building built with traditional methods of construction was just over 6% better (Piroozfar et al. 2009).

![Figure 1: The predicted monthly heating loads in kWh with respect to the employed construction methods; Adapted from (Piroozfar et al. 2009).](image)

Whilst the potential benefits of adopting prefabrication in the construction industry are highly discussed, barriers that may be encountered when utilising the innovative constructing method are affecting the uptake in the UK housing construction industry. The potential of limiting design flexibility and customisation (Hashemi & Hadjri 2013) in addition to the steep perceived costs to implement are some of the said barriers that the industry is encountering (Lovell & Smith 2010). Furthermore, a fear of change (Phillipson 2001), engineering obstacles, such as embedding mechanical and electrical (M&E) services in cast in-situ concrete (Rashid 2009) and a larger lead time, may provide challenging to the UK housing industry (Tam et al 2007).

Even though continuous, incremental innovation has not been important for the average UK house builder’s continuity, a much more pro-active approach to innovation will be needed in the future in order to stay competitive (Barlow 1999). It is not known what the
future for prefabrication in the UK holds, but the number, location and capacity of plants for the production of elements must be considered thoroughly in order for prefab to be successfully implemented (Warszawski & Ishai 1982).

A thorough investigation is required in the area of offsite construction in the UK as the literature surrounding this topic is limited on current views and execution of the practice. A questionnaire had been designed to evaluate the current situation of MMC and the views of practising construction professionals in UK housing construction industry. Case studies had also been conducted in order to provide information on current industry practices. The questionnaire results reveal several key barriers which are hindering the adoption of the innovative solution that prefabrication presents in the United Kingdom. The case study results identify key reasons as to why prefab is currently being integrated by certain house builders into their traditional house building process.

2 Methodology

Secondary data was collected through the analysis of a range of sources, including conference papers, reports, journal articles and books in order to carry out a detailed evaluation on the current content that is available. Primary data was also collected through the use of questionnaires. The questionnaire aimed to recognise the opinions of house constructing practitioners on prefabrication in the construction industry.

A pilot study was conducted to evaluate the time required and to ensure requirements for each question had been met. The questionnaire was distributed amongst targeted individuals from medium/large house builders. It was assumed that medium and large house builder would have more access to resources allowing them to deal with large scale projects and thus, may share more insight. Professions that had been targeted included projects managers, construction managers and quantity surveyors which had been chosen in order to represent the key job roles that a UK house builder of a substantial size would hold. The questionnaire consisted of four key sections and was primarily made up of three question types:

- Dichotomous, whereby the question offers a ‘yes’ or a ‘no’
- Multiple choice whereby the question offers three or more choices
- Likert scale where the respondent shows the amount of agreement or disagreement (Strongly agree to strongly disagree).

Whereas Section A aimed to gauge the participant’s background including their industry experience, profession, gender and their companies’ capabilities, the subsequent questionnaire consisted of three following sections that had been defined as key criteria that had been based on the findings of similar research questionnaires. Section B captured the level of awareness that practitioners have of prefabrication in the construction industry; Section C aimed to capture the views and opinions of practitioners in the construction industry on the application and practise of prefabrication and Section D had been designed to explore the views and opinions regarding the future of prefabrication in the housing construction industry.

An investigation of three case studies were also been conducted. The first case study utilised prefabricated roof panels. The second and third case study reviewed the construction of dwellings that had been constructed at BRE’s Innovation Village, an innovation park rich in Modern Methods of Construction (MMC) located at Watford, UK.
2.1 2.1 Questionnaire distribution and analysis
Questionnaires were sent to 174 specific professionals who had a period of 31 days to return the completed questionnaire. Out of the questionnaires sent, there were 54 respondents which equates to a 31% response rate. The majority of those were project managers (20%), construction managers (19%) and quantity surveyors (13%). Only two directors (4%) and three general managers (6%) responded to the questionnaire. Out of the total respondents, 56% were male and 44% were female.

When it came to industry experience, the highest amount of respondents (20%) had between 7 and 10 years and 17% of respondents had 15 years or more industry experience. 6% had 1 year or less and a further 6% had between 1 and 2 years. A total of 4 respondents (7%) worked for a company that constructed up to 2,000 houses in the previous year, 13 respondents (24%) selected ‘between 7,500 to 10,000’ and the most common option selected had been between 10,000 to 15,000. Statistical Package for Social Sciences (SPSS) had been used to analyse the data and to examine the significance of the results. The results in over 94% of cases were statistically significant to P < 0.05. The results have been rounded to the nearest 1%.

3 Results of Questionnaire
Whereas Section B (3.1) explores the level of awareness that practitioners have of prefabrication in the construction industry, Section C (3.2) aims to capture the views and opinions on the application and practise of prefabrication in the construction industry. Section D (3.3) aims to explore the views and opinions regarding the future of prefabrication in the house construction industry.

3.1 3.1 Prefabrication Awareness
All respondents, to a certain extent, had considered themselves as aware of prefabrication in the construction industry. When it comes to the most advantageous aspects of prefab, the respondents considered time improvements and the potential of minimising site-based accidents came out on top with an average weighted score of 3.8. When asked which advantage they thought would be the most beneficial to their organisation at this moment in time, time improvements was ranked as the highest benefit (28%).

![Advantages of prefabrication](image)

**Figure 2:** Advantages of prefabrication.
3.2 Views and Awareness
As a whole, responses indicated that prefab was seen as beneficial to the overall construction industry however, the majority of respondents (35%) said that they never suggest using prefabrication and a further 28% of respondents selected rarely. The majority were of the opinion that more could be done to apply prefab in projects that they worked on (98%) whereas only 2% of respondents had been of the opposite opinion.

3.3 Future of Prefabrication
When it came to denote the degree to what they believed were the biggest barriers that prefab in the UK construction industry was facing, extra costs has been rated the highest with an average weighting of 3.91. Other factors included potential limitations in site space (2.8) and engineering issues (3.69), with the lowest rated factor being no demand for prefab (2.59). There had been a 100% agreement that more could be done to raise awareness in regards to prefabrication in the construction industry and the majority
of respondents said that government subsidies would be the most likely incentive to increase prefab in the UK house building industry in the shortest time possible.

![Barriers affecting prefabrication](image)

**Figure 5:** Barriers of prefabrication.

![Incentives to maximise prefabrication usage](image)

**Figure 6:** Incentives that would increase the use of prefabrication in the house building industry.

4 Case Studies

4.1 Barratt Homes

With the increasing demand in housing, Barratt homes, one of the largest residential property development companies in the UK, have explored many prefabrication options. One system that has been adopted into Barratt’s traditional housing construction is the RoofSpace I-Roof system whereby panelised roofing panels replaces the traditional construction process.
The RoofSpace I-Roof™ System is an innovative and sustainable timber engineered panelised roof system. It encapsulates the roof space of dwellings in order to provide habitable and cost efficient living spaces. There have been several other developments that Barratt have constructed in the surrounding areas of Ashford, the majority of which have utilised the I-Roof system extensively.

Barratt homes started using the I-Roof system around 7 years ago in order to design steels out of certain roof types. The steels posed a steep health and safety risk as they would occasionally be dislodged by adverse weather conditions. Furthermore, the steels would often account for many reported minor injustices such as cuts. Other safety benefits include a reduction in working at height and the reduced risk of a gable block work collapsing (Cook 2016).

Panels are fixed down to the wall plate, which is bedded in mortar and fixed to the block work using L-shaped restraining straps. Potential savings of days and even weeks can be made in a typical build programme. Barratt now installs over 1000 panelised roof systems per year (Cook 2016).
4.2 Hanson Ecohouse

Hanson Ecohouse, situated at BRE’s Innovation Park, is home to some of the world’s most sustainable buildings. Built in 2007, the Hanson Ecohouse is a detached, 117 square metre (sq m) two story house, designed to showcase the latest developments in masonry construction and smart technology. It was the first of its kind to achieve a Code Level 4 under the Code for Sustainable Homes in which offsite construction played a significant role (McCann 2016).

The dwelling makes extensive use of prefabricated walls, a composite ground floor system and a precast concrete staircase. High thermal mass levels have been achieved with prefabricated elements which will allow the building to store heat during warm periods and release it during cooler spells. The energy saved by the thermal mass in a masonry house can help significantly to reduce the carbon dioxide emissions over the life of the building (McCann 2016).
The structural walls of Hanson Ecohouse have been constructed using the Hanson’s quick build walling system. The external walling system comprises of pre-insulated and pre-finished brick and cavity wall panels. Once the panels had been factory made and delivered, a crane had been used to position them into place. Ground panels were then mortar jointed directly onto preformed foundation walls. The use of prefabricated components led to the timely completion of the dwelling (McCann 2016).

4.3 Sigma Rexel House
The Sigma Rexel house comprises of two separate dwellings and was the first house in the UK to achieve a Code Level 5 under the Code for Sustainable Homes. The design addressed the need for high density living with 4 levels having been designed over the size of a large three story house. This resulted in minimising the building’s footprint and maximising affordability (McCann 2016).

Similar to Hanson’s Ecohouse, the Sigma Rexel house utilised offsite construction extensively in order to reach a high level of sustainability whereby a 100% reduction in carbon dioxide emissions have been achieved. The panelised system employed had factory fitted insulation, air membrane and service cavity batons ready from the supplier. The engineered timber floor had been factory pre-made with pre-fitted decking installed. Other elements that had been factory made included the foundation piles, precast ground beams and the pre-insulated roof cassette system (McCann 2016).
In just 10 working days, the main superstructure had been made wind and water tight and took a total of 10 weeks to complete. The fast build time can be directly related to the extensive use of prefabricated components (McCann 2016).

5 Discussions

The results of the questionnaire has identified key issues that need to be highlighted before prefabrication can be established as a common form of construction in the UK housing construction industry. According to the results, the most advantageous aspect of prefabrication is a reduction in potential site-based accidents and time improvements. Previous studies (Samuelsson Brown et al 2003; Goodier & Gibb 2007; Hashemi 2015) have also found that respondents to a similar question rated a lower construction time as the most important factor that prefabrication brings. In the Sigma Rexel house and Hanson Ecohouse, the use of prefabricated components have been linked to the quick erection, further supporting the perception that prefabrication allows for time advantages when compared to conventional construction techniques.

Even though previous studies have not identified the potential for minimising site-based accidents as a main reason for utilising prefab, the findings of this research show that professionals working in the construction industry are becoming more health and safety conscious and that the overall opinions in construction professionals is changing. This is further supported by Barratt Homes having introduced prefab to their traditional house building process in order to minimise health and safety risks (Cook 2016). Transferring much of the construction programme from an open site to a controlled factory setting may greatly reduce on-site worker activity and the associated risks of site-based accidents (Blismas et al 2006). The opportunity for standardisation came in last place (9th). Professionals in the construction industry need to recognise the importance of standardisation as it is directly related to the overall costs of prefabricated components, therefore by increasing the standardisation of products will lead to an enhanced value for money.
Even though prefab is widely recognised in the construction industry with all respondents being aware to a certain extent, most respondents stated that they never suggest using prefab in place of traditional methods. The lack of suggestion might be due to the respondents being worried of negative criticism by suggesting an unconventional method of construction.

Higher capital costs, whether perceived or real, had been considered as the most significant barrier that prefabrication is currently facing in the construction industry. The findings of previous questionnaire surveys (Goodier & Gibb 2007; Pan et al 2008; Jallion & Poon 2008) further supported that increased costs had been considered as the biggest barrier affecting prefab. Costs of integrating innovative processes such as offsite construction to the UK housing industry may lend costly (Lovell & Smith 2010) and with it being the highest rated factor suggests that the industry is more fixated on costs rather than on other potential benefits prefab may bring. The construction industry should also focus more on important factors that need addressing such as achieving sustainability targets and meeting housing demands in order to progress. No demand for prefabrication came in last which further emphasises that there is a need for prefabrication in the industry however there is resistance to shift.

There was a 100% agreement that more could be done to raise awareness in regards to prefabrication in the construction industry and the majority of respondents believed that government subsidies would be the quickest way in which the uptake for prefab would increase within UK housing construction industry. Moreover, 20% of respondents were of the opinion that other forms of financial incentives were required in order to increase the use of prefab. These two factors are both financially orientated and tie in with previous findings of this research, that the industry is financially driven.

The results of the questionnaire indicate that many respondents are of the opinion that the use of prefab would increase in the future, however, several respondents mentioned perceived hindrances associated with prefab needed addressing before there is an increase in uptake with one respondent mentioning that lead times need to be significantly lowered. Construction is in a period of rapid cultural change accompanied by the introduction of new technologies and new ways of organising construction activities (Agapiou et al 1995). The future of offsite construction is dependent on many factors, not least of which is a better understanding of the construction process and its associated costs (Blismas & Wakefield 2009).

6 Conclusion
Considering the three main challenges that the UK is currently experiencing; skilled labour shortage; a housing shortfall and sustainability targets, the use of offsite methods of construction would potentially improve the current situation. However, the results of this study have suggested that prefabrication has many barriers to overcome before it can be considered as a mainstream construction technique, including costs, addressing lead times and the need to retain a degree of flexibility for design changes.

In order to improve current conditions and to increase housing production to meet demands, there is a prerequisite for cultural change in the construction industry, one that is widely recognised for the non-collaborative, blame culture and conservatism which hinders diffusion of innovation. In order to drive the necessary cultural change, there is a requirement for more dedication on behalf of construction workers alongside a degree of commitment from top management. There also needs to be commitment to remediate and solve the current issues that the industry is experiencing and a more open and proactive
approach in attempting to modify the traditional form of construction for the better. Further research may seek to conduct interviews with a wide range of stakeholders which could lead to identifying new emerging issues and trends. Visiting well-established prefabrication manufacturing sites in the UK would also help to understand the available offsite products as well as investigate the barriers from the manufacturers’ perspective.

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ENERGY AND LOW-INCOME TROPICAL HOUSING IN TANZANIA

Bryony Coombs¹, Arman Hashemi² & Heather Cruickshank³

¹ Department of Engineering, University of Cambridge, UK & Balfour Beatty, London, UK, coombsbryony@gmail.com
² School of Environment and Technology, University of Brighton, UK, A.Hashemi@brighton.ac.uk
³ Smart Villages, Cambridge, UK, heather@es4v.org

Abstract: Low-income housing in Tanzania is traditionally made from mud and thatch. With thatch having a typical life span of 2-7 years and mangrove poles 5-15 years, low durability is identified as the key issue with the traditional low-income house design. This paper studies the financial and social implications, embodied energy (EE) and human energy (HE) of a variety of materials in a bid to identify both the positive and negative impacts of each material substitution on the overall design, the environment and the local community. Using primary data collected from houses in the Mbweni district of Dar es Salaam and The Inventory of Carbon and Energy to calculate EE, a qualitative and quantitative assessment of each material is made. 47% of residents questioned in Tanzania, identified low durability to be the key issue with their mud house, with design changes which address this issue therefore affecting the largest share of the population. Stabilised bricks are identified as the key material substitution that should be adopted by local people, they perform well in terms of improved durability, financial and environmental considerations, and have the potential to be socially beneficial as well. This research identifies the social considerations to be key to understanding how local people will respond to the suggested material substitutions and whether they are likely to be adopted in the future. Whilst the environmental considerations are important, this is not a concept local people can relate to and does not affect their day-to-day lives as much as financial and social implications. It is extremely difficult and ethically questionable, especially in communities with people living close to poverty, to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment.

Keywords: Low-income, Housing, Embodied Energy, Building Materials, Tanzania
1 Introduction

Tanzania is one of the least developed countries in the world, with a Human Development Index ranking of 159/187. It has a land area of 945,203 km², a population of 49.6 million with an average life expectancy of 61 years (World Fact Book 2014). Dar es Salaam is Tanzania's largest city, located in the tropical region on the east coast, with a population of 3.6 million. 70% of the population of Tanzania live in rural areas (National Bureau of Statistics 2013). 78% of houses in Tanzania are built with mud walls (Tanzania National Bureau of Statistics 2011), indicating that projects addressing problems associated with the mud house designs carry the potential to impact a large portion of the country's population.

There are a range of problems associated with the use of mud and thatch in house construction, as they fail to meet the needs of residents. The availability of photos and house dimensions for mud house designs is limited. There is no clear identification of the key issue surrounding the traditional design and much of the previous research does not discuss the social considerations of low-income housing or provide sufficient focus on the needs of the residents these problems affect daily. Hence there is a clear need to obtain primary data focusing on obtaining information about a large range of mud houses and the views and opinions of the residents, whilst looking into material substitutions to be made to the traditional design. Studying the Embodied Energy (EE) of building materials used in low-income housing allows comparisons of the environmental impact of certain designs/materials to be drawn (Hashemi et al. 2015). The level of development in a country or area affects the efficiency of industry, efficiency of material transportation and the processing techniques used for materials and hence careful consideration is needed to select adoptable values of EE for materials in Tanzania. Whilst The Inventory of Carbon and Energy (ICE) Version 2.0. details the EE of construction materials in the UK (Hammond 2011) no such database is available for Tanzania. To this end, this paper assesses the environmental, financial and social impact of making material changes to a traditional low-income house design in Tanzania, with particular focus on the direct effect on the local community. Considering these aspects side by side is what makes this project unique.

1.1 Low-income house design

Low-income housing in Tanzania has many forms. Traditionally, mud and thatch were used for house construction as the materials could be sourced locally for little or no monetary cost. In recent years, especially in semi-rural areas of Tanzania, there has been a move away from the traditional design outlined in Figure 1. This is due in part to the increased difficulty associated with sourcing traditional materials, paired with increased availability of and desire for modern materials, with concrete becoming a ‘wealth status indicator,’ as evidenced by the field work.

Figure 1: Photo and layout of traditional mud house, House 6
Almost all of the observed low-income houses were made from mud and pole walls covered with a thatch roof. The dimensions of the houses that were surveyed by the author during the field work were noted and the average dimensions computed. ‘House 6’ (Figure.1.) from the survey matches, almost exactly, the dimensions of the average house calculated. This two room house has therefore been taken for this research as the typical traditional house design, on which design modifications are based.

The walls are made from mangrove poles dug vertically into the ground, strung together with bamboo poles and the frame (Figure.2.) filled with mud. The roof is made from coconut palm fronds, woven together and built into a pitch, supported by mangrove poles (Wells 1998). Iron sheeting is commonly placed at the ridge of the roof, as it is difficult to get a perfect seal between the two slopes. Salvaged material is often used to patch up sections of the house, in a bid to improve the overall durability. Traditionally the houses are built by the local community, using free collected materials or materials bought from local traders, keeping money exchange within the community. The house is constructed in a collaborative effort by local people for convenience, ease of repair and to reduce labour costs.

Theoretically, thatch lasts 2-7 years and mangrove poles 5-15 years (Wells 1998), with thatch therefore limiting the durability of the traditional design. Table.1. outlines the properties of traditional construction materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove Poles</td>
<td>Strong for weight-bearing and naturally resistant to rot and termite attack</td>
<td>Expensive to buy and becoming increasingly difficult to source locally, due to environmental regulations</td>
</tr>
<tr>
<td>Bamboo Poles</td>
<td>Lightweight and strong for linking vertical poles together</td>
<td></td>
</tr>
<tr>
<td>Mud</td>
<td>Readily available and cheap</td>
<td>Easily worn away during the rainy season</td>
</tr>
<tr>
<td>Coconut Palm Fronds (Thatch)</td>
<td>Highly insulating with a low thermal capacity</td>
<td>Low durability during the rainy season</td>
</tr>
<tr>
<td></td>
<td>Compliments thermal properties of mud</td>
<td>Difficult to obtain a strong seal between the two slopes of the roof</td>
</tr>
</tbody>
</table>
2 Methodology

Site visits and surveys were carried out in collaboration with The National Housing and Building Research Agency (NHBRA) collecting data from houses in small villages in the Mbweni district, north of Dar es Salaam.

- Housing physical surveys: identified typical dimensions (including floor plan, elevation dimensions and photos) of traditional mud houses in Tanzania. This was necessary due to limited availability of data to show the variations between different mud house designs. Each house was numbered and the collected information is summarised in Table.3.
- Householder questionnaire survey: identified how people use their houses and what they identify as the main issues with their current house design. Information was obtained through non-intrusive semi-structured interviews with extra information being obtained through more casual conversations with locals. The findings are summarised in Table.3.
- Strength and porosity tests: were completed on a range of construction blocks, using methodology identical to that used by The NHBRA to complete continuous testing on the stabilised mud bricks that they produce.

2.1 Embodied Energy (EE)

Papers which support the idea that no database is 100% accurate show that even countries with extensive research into EE do not have highly accurate or reliable values for all materials (Dixit 2010). If reliable information for developed countries is difficult to obtain, this reduces the likelihood of finding usable values for Tanzania, due to significantly less research in this field in developing countries. The following resources detail EE values in different countries:

- UK – The Inventory of Carbon and Energy, Version.2.0 (Hammond 2011)
- New Zealand – Alcorn and Baird (Alcorn 1996)
- Canada – (Canadian Architect 2015)
- India – Various Reports (Reddy 2003; Shukla 2008)

‘Embodied Energy and CO$_2$ Analyses of Mud-brick and Cement-block Houses’ (Abanda 2014:18-40) looks at the EE of a mud-brick and concrete house in Cameroon, using values for EE taken from the ICE. The use of this database in Cameroon would suggest these values are also accurate estimates of EE values in Tanzania. ‘Embodied Energy Analysis of Adobe House’ (Shukla 2008:755-761) shows the EE of constituent parts of an adobe house in India. The analysis assumes that the EE of mud is zero, because it is dug out of the ground on site with zero transportation or commercial excavation costs. Shukla identified that 12% of the total EE of an adobe house is consumed making repairs. The paper therefore supports the need to consider ‘human energy’ (HE) alongside EE as well as assessing the energy input for repairs and not just the initial construction, turning the focus back to the durability of designs.

The concepts identified above, combined with independent research, confirm that using the ICE v.2.0 for values of EE in Tanzania will not produce large errors. Table.2. shows the ICE v2.0 EE values of the common construction materials used in low-income housing in Tanzania. The relatively large ranges and standard deviations for each material show the huge variation between EE of the same material within a single country, highlighting the difficulty in pinpointing a single value of EE for materials in a country where data is readily available. It is likely that the value of EE for a material in Tanzania will fall somewhere inside the range of values documented in the ICE. Therefore, the average EE values given in the ICE are used in this study for materials in Tanzania. Whilst it is important that the EE values used are as accurate as possible, because the focus is on...
comparisons between different materials studied, as long as information from the same source is used for each material, a reliable comparison can be drawn.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average EE (MJ/kg)</th>
<th>No of Samples</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>5.32</td>
<td>94</td>
<td>2.05</td>
<td>1.42</td>
<td>11.73</td>
<td>10.31</td>
</tr>
<tr>
<td>Sand</td>
<td>0.21</td>
<td>18</td>
<td>0.23</td>
<td>0.02</td>
<td>0.63</td>
<td>0.61</td>
</tr>
<tr>
<td>Iron</td>
<td>24.62</td>
<td>21</td>
<td>7.5</td>
<td>11.7</td>
<td>36.3</td>
<td>24.6</td>
</tr>
<tr>
<td>Concrete (General)</td>
<td>3.01</td>
<td>112</td>
<td>9.07</td>
<td>0.07</td>
<td>92.5</td>
<td>92.43</td>
</tr>
<tr>
<td>Steel*</td>
<td>21.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Timber</td>
<td>7.11</td>
<td>55</td>
<td>4.8</td>
<td>0.72</td>
<td>21.3</td>
<td>20.58</td>
</tr>
</tbody>
</table>

*Uses World Typical Value (39% recycled)

It is noted that ‘the single most important factor in reducing the impact of EE is to design long life, durable and adaptable buildings. Buildings should aim to use materials that have lower EE’ (Strine Environments 2015). So whilst this project doesn’t focus on the full life cycle energy analysis of houses, there are key long-term implications of material choice which should be considered. Although the initial mud house contains less energy than a more durable design, if it needs to be repaired every 2 years then the energy (especially human energy) required to make these repairs must be considered as well.

3 Results

3.1 Field Work Results

Table 3. summarizes the information recorded in the field from the housing surveys and questionnaires. These results summarise key information about house construction and maintenance, house use, house dimensions and the key problems with mud house designs. The results clearly show that low durability is the key problem with low-income housing, this forms the basis of the research presented in this paper.

<table>
<thead>
<tr>
<th>Detail (n=Number of houses surveyed)</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of material (n=16)</td>
<td>Bought</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Found</td>
<td>5</td>
</tr>
<tr>
<td>How often are repairs made? (n=17)</td>
<td>1.8 years</td>
<td>-</td>
</tr>
<tr>
<td>Where do you cook? (n=17)</td>
<td>Inside</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Outside</td>
<td>10</td>
</tr>
<tr>
<td>What fuel do you use? (n=12)</td>
<td>Wood</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Charcoal</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>2</td>
</tr>
<tr>
<td>Average number of people living in the house</td>
<td>3.8 ppl</td>
<td>-</td>
</tr>
<tr>
<td>Biggest problem with the house (n=19)</td>
<td>Low durability</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>High internal temperature</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Poor ventilation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Low lighting</td>
<td>2</td>
</tr>
</tbody>
</table>
3.2 Calculation Results

Using previous research combined with primary data from the field, calculations of the cost and EE of constituent elements for each house design were calculated, based on the house outlined in Figure 1. Table 4 provides a summary of the values associated with each material for each element of the house, allowing comparisons of durability and social and environmental impacts to be drawn.

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>Material Cost (£)$^1$</th>
<th>Embodied Energy of Material</th>
<th>Embodied Energy for whole house (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>Mud</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Stabilised Mud Brick</td>
<td>206.58</td>
<td>6.67 MJ/Block</td>
<td>10.44</td>
</tr>
<tr>
<td></td>
<td>Concrete Block</td>
<td>506.52</td>
<td>14.8 MJ/Block</td>
<td>18.59</td>
</tr>
<tr>
<td>Roof$^2$</td>
<td>Thatch</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Iron</td>
<td>129.74</td>
<td>279.59 MJ/sheet</td>
<td>6.08</td>
</tr>
<tr>
<td></td>
<td>Sisal Reinforced Tiles</td>
<td>200.22</td>
<td>3.44 MJ/tile</td>
<td>10.59</td>
</tr>
<tr>
<td>Floor</td>
<td>Mud</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>1,222.10</td>
<td>7.22 MJ/m$^2$</td>
<td>78.38</td>
</tr>
</tbody>
</table>

4 Findings

4.1 Durability

From the housing survey, the mud and thatch houses required repair every 1.8 years, on average, with the main cause for repair being problems with the thatch roof. Theoretically, thatch lasts 2-7 years and mangrove poles 5-15 years (Wells 1998). Common variations on the traditional design aim to improve durability, requiring less continuous repair, but come with other issues.

- Concrete blocks have a cement to sand ratio of 1:16 and an ultimate compressive strength (UCS) of 1.1MN/m$^2$.
- Stabilised mud bricks have a cement to soil ratio of 1:12 and an UCS of 6.5MN/m$^2$, almost 6 times that of the concrete blocks.

Whilst these figures do not directly measure durability, they indicate the block’s ability to withstand loading/erosion. During the hydration of cement tobermorite gel is formed (Brunauer 1962), giving cement-containing elements their strength. Hence blocks with a higher cement content should be more durable. Quality control is recognised as a key influence over durability of buildings worldwide (Gjørv 2015). In Tanzania many construction materials are made using a variety of techniques in a largely unregulated environment.

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$^1$ 1000 Tzs = £0.33. Exchange rate taken on 11th May 2015 at 13:06. (XE 2015)

$^2$ Timber beams used for roof designs have an EE=61.9MJ/m
manner, like the concrete blocks studied for this research. The NHBRA tiles and bricks are either built in the lab or made on site by trained locals.

Considering all these points the stabilised mud bricks are expected to be the most durable wall material, followed by concrete blocks and then mud. It is difficult to compare the roof materials quantitatively, due to limited strength data.

- Thatch is the key element that reduces the durability of traditional designs. It is readily attacked by termites, it also rots and leaks in high rain and thus offers little protection to the elements.
- Iron sheeting is susceptible to rust, but is easy to assemble to form a sturdy, protective roof and easily adaptable for houses with a variety of wall materials. Yet, it should be noted that unlike thatch, iron sheeting may have negative effects on thermal comfort inside low-income houses (Hashemi 2016).
- Stabilised roof tiles are only compatible with blockwork walls that have the strength to support them.
- Both the iron and tile roof materials are waterproof and therefore have the capability to improve the durability of both the walls and foundations by directing rainwater away from these elements.

4.2 Financial Implications

Mud and thatch houses traditionally have zero material costs. With the recent implementation of conservation projects, however, the availability of these ‘free’ building materials has been reduced. Considering that it may become necessary to pay for these low durability materials, investments in the development of higher durability, similar function materials may prove worthwhile and should be investigated.

- The materials required to build concrete walls cost approximately 2.5 times that of the stabilised block design, with 62% of the cost of the concrete walls due to the reinforced concrete beam, a feature which is not required for the stabilised brick wall due to the bricks’ interlocking nature.
- The sisal tile roof design is 1.6 times more expensive than the iron roof design, due to the large quantity of timber needed.
- Installing an iron roof is the single cheapest design change, as all other designs require the installation of a concrete foundation first, for safety reasons, and for this reason iron sheeting is seen as the preferred roof material substitution.

4.3 Embodied Energy

The EE of the different elements of each design can be used to assess their relative environmental impacts, as summarised in Table.4, and discussed below:

- The EE of the concrete wall design is approximately 1.8 times that of the stabilised brick wall design, with the concrete beam contributing to 64% of the total EE of the concrete design.
- The sisal tile roof design contains almost twice the EE of the iron roof but the sisal tiles contain 1.7GJ EE whereas the iron sheets contain 3.9GJ EE in total. The key difference is the nature of the timber support structure which requires significantly more timber.
- The design improvement with the highest EE is the concrete foundation containing 78.4GJ EE, but is also expected to be the most durable design change. This raises the issue of whether this financial and EE investment in a concrete foundation is worthwhile in terms of return in improved durability.

The EE of a concrete foundation is 13 times the EE of an iron roof. It is unlikely that installing a concrete foundation rather than an iron roof improves the durability of the
house 13 fold, as this still leaves thatch as the key determiner of durability. Hence a concrete foundation is not an environmentally beneficial investment.

4.4 Social Considerations

Social considerations are quantified by Human Energy (HE) calculations. HE comes from:
- Extraction, processing and transportation of materials;
- Construction of house elements;
- Repair and maintenance.

HE inputs have two key considerations in this study:
1) The HE input, whilst significantly lower than the EE, contributes to the overall energy required for house construction. Due to the low EE values of traditional materials, the HE contribution forms a larger proportion of the overall energy than it would for more EE intense materials.
2) The main problem identified with low-income housing in Tanzania is low durability. Residents resent having to repair and rebuild their houses. The relatively high HE input needed to maintain a mud house makes it less desirable than more durable designs, despite their higher EE and financial cost.

According to CIBSE (2015), a human produces 233 Watts/m², when lifting 50 kg bags (activity taken as closest to that of mud house construction). Multiplying this by 1.8 gives the energy output for a standard human body as 419.4 Watts. Using these figures it is calculated that a human produces 12.1MJ of energy during an 8 hour working day during the house construction. Using simplified assumptions of the human working hours (Kwanama 2015) put in to the mud and thatch house construction, the HE input can be calculated (Table.5.).

<table>
<thead>
<tr>
<th>No of Days</th>
<th>Number of People</th>
<th>Activity</th>
<th>Human Energy (MJ)</th>
<th>Design Element</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>Collect poles and stripes</td>
<td>72.6</td>
<td>Walls</td>
<td>Material Extraction and Transportation</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Dig holes in the ground</td>
<td>72.6</td>
<td>Walls</td>
<td>Construction</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>Erect poles</td>
<td>36.3</td>
<td>Walls</td>
<td>Construction</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Fix stripes</td>
<td>72.6</td>
<td>Walls</td>
<td>Construction</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Look for rafters for roof</td>
<td>72.6</td>
<td>Roof</td>
<td>Material Extraction and Transportation</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Collect and prepare thatch</td>
<td>72.6</td>
<td>Roof</td>
<td>Material Extraction and Transportation</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Fix stripes on roofing poles</td>
<td>72.6</td>
<td>Roof</td>
<td>Construction</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>Digging mud from ground &amp; putting on the walls</td>
<td>580.8</td>
<td>Walls</td>
<td>Construction &amp; Material Extraction and Transportation</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>Construct roof from thatch</td>
<td>435.6</td>
<td>Roof</td>
<td>Construction</td>
</tr>
<tr>
<td>1/2</td>
<td>12</td>
<td>Gather all the materials and move them to house location</td>
<td>72.6</td>
<td>Walls/Roof</td>
<td>Material Extraction and Transportation</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1560.9</td>
</tr>
</tbody>
</table>
This shows that:

- 580.8MJ of HE is used to extract and transport the raw materials used for the house design, assuming half of the energy for putting the mud onto the walls is used for digging the mud from the ground.
- The HE of extracting and transporting the materials constitutes 37% of the total HE of the entire house design – 399.3MJ in the wall materials and 181.5MJ in the roof.
- 212.9MJ of HE is required for repairs (17.6 human working days), using Shukla’s (2008:755-761) principle that 12% of the total EE is for repair work, as all energy input is from HE.

The HE for the mud and thatch house is 1.5% of the EE of a concrete and iron house which, whilst small, is significant when you consider that all of this energy is from human exertion. HE is a value that quantifies the efforts of local people. Doubling the HE of a design has more direct impact on local people than doubling the EE. Low durability was identified as the key issue with mud houses in Tanzania, because of the inconvenience that house repairs pose to the residents. Overall, considering materials and construction the thatch roof has 689.7MJ HE and the mud walls 871.2MJ HE. The average lifetime of thatch is 4.5 years and of mud walls is 10 years. Therefore thatch roofs have a higher HE input (153.3MJ HE per year) than mud walls (87.1MJ HE per year) relative to their durability. This confirms why iron roofs are commonly installed in Tanzania. An iron roof design takes equal or less time to construct, compared with a thatch roof, but requires fewer repairs and is significantly more durable.

4.5 Discussion

The use of concrete blocks, stabilised bricks and sisal fibre roof tiles all require the installation of a concrete foundation, for safety reasons. Installing a concrete foundation has huge durability benefits as shown by House 20 (Figure.3.) which was built 40-50 years ago and since then has required little repair expect for “sometimes filling in the gaps in the walls with more mud”. As this design change needs to be installed first, the traditional design cannot be gradually improved using the methods studied, highlighting the need for other small-scale modifications, which do not require concrete foundations. Protective measures, such as covering mud walls with plaster or paint and using baked mud bricks should therefore be considered. When a mud house is sold, the buyer pays for the cost of the plot of land the house sits on, so investments made to make small scale improvements to the design using plaster and paint, are not recovered upon sale. If there is a concrete foundation or brick/block walls, extra revenue is obtained in the sale, recovering some of the initial investment. Therefore, there is a point at which small-scale improvements to mud houses become economically unviable in the long-term compared with block/brick designs. In order to save enough money to make substantial design improvements families stop making repairs to their current houses and save up money to invest in more durable designs, causing families to live in extremely poor conditions with all their hope pinned on a better house in the future.
The key concepts outlined in Ethics in Engineering Practice and Research (Whitbeck 1998) highlight the moral obligations researchers and engineers carry. In the context of this research this book raises a key question. Ethically, is it right to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment, especially in communities with people living close to poverty? Whilst environmental considerations are important, and in terms of global sustainability environmental considerations should form part of the basis of all engineering decisions this should not be the key driver in these communities in Tanzania. The EE of low-income, single-storey houses is insignificant compared to the EE of the materials used for buildings in developing countries. Tanzania will be better equipped to address environmental issues, once the majority of people in the country have acceptable living conditions and are no longer living in poverty. What is most important is that the new designs bring benefits to the local people, fix the key issue (low durability) they have with the current design whilst reducing the negative social and financial impacts as much as possible. These are also key drivers for a design being accepted by the local community as they have a direct impact on their lives. Ultimately homeowners will form their own opinions about a material or design based on the return in improved durability obtained for a given financial or HE input and this will determine its success.

5 Conclusions
Following the comparison of a range of material substitutions made from the traditional mud and thatch house design, the following conclusions can be drawn:

- Low durability is the key problem with low-income housing in Tanzania (confirmed by 47% of residents surveyed).
- Whilst no material substitution is perfect, The NHBRA stabilised bricks perform well in terms of improved durability compared to mud walls with lower financial and environmental costs than concrete walls. This is identified as the key material substitution which should be adopted, for its financial, environmental and social benefits over mud and concrete walls.
- The installation of an iron roof, whilst having huge positive impacts on the durability of a mud walled house, is both the cheapest and most environmentally friendly material substitution studied. As thatch is the least durable material this highlights why iron is commonly substituted for thatch in mud houses.
- Whilst the environmental impact of a design change is not something to which local people can easily relate, the social considerations are particularly important. The
opinions that local people have about a material decides whether that design will be accepted and adopted, which ultimately determines the ‘success’ of a design change.

- It is extremely difficult and ethically questionable to expect someone to adopt a design which requires more effort/money on their part, just because it is better for the environment, especially in communities with people living close to poverty.

This work does not focus solely on one single aspect of a design, but incorporates social, environmental and financial considerations, showing that future research should give heightened consideration to priorities of local people. Continuing on from this work, the following is suggested:

- Precise calculation of the HE input for each material substitution suggested;
- Establish precise maintenance regimes for each of the materials and designs suggested, providing a better understanding of the durability of each material, allowing durability comparisons to be more accurate;
- Further interviewing of local people to obtain opinions on the material substitutions suggested in this project, to establish whether people are willing to invest money in the suggested material changes.
- Identification of any other material substitutions which should be analysed using the above framework.

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ADOPTION OF RETROFIT STRATEGIES FOR THE HOUSING SECTOR IN NORTHERN CYPRUS

Bertug Ozarisoy\textsuperscript{1} & Hasim Altan\textsuperscript{2}

\textsuperscript{1} School of Architecture, Computing & Engineering, University of East London, London, United Kingdom, ozarisoyb@gmail.com
\textsuperscript{2} Department of Architectural Engineering, University of Sharjah, Sharjah, United Arab Emirates, hasimaltan@gmail.com

Abstract: This research project is undertaken in the Turkish Republic of Northern Cyprus (T.R.N.C.). The study focuses on identifying refurbishment activities capable of diagnosing and detecting the underlying problems alongside the challenges offered by the buildings' typology in addition to identifying the correct construction materials in the refurbishment process, which allow for the maximisation of expected energy savings. The objective of the research is to investigate the occupants' behaviour and role in the refurbishment activity by exploring how and why occupants decide to change building components and how to understand why and how occupants consider using energy-efficient measurements. The housing estates are chosen from 22 different projects in four different regions of the T.R.N.C. that include urban and suburban areas. There is, therefore, a broad representation of the common drivers in the property market, each with different levels of refurbishment activity and this is coupled with different samplings from different climatic regions within the country. The study is conducted through semi-structured interviews to identify occupants' behaviour as it is associated with refurbishment activity. This paper presents the results of semi-structured interviews with 70 homeowners in a selected group of 22 housing estates in five different parts of the T.R.N.C. Alongside the construction process and its impact on the environment, the results point out the need for control mechanisms in the housing sector to promote and support the adoption of retrofit strategies and to minimize non-controlled refurbishment activities, in line with diagnostic information of the selected buildings. The expected solutions should be effective, environmentally acceptable and feasible, given the type of housing projects under review, with due regard for their location, the climatic conditions within which they were undertaken, the socio-economic standing of the house owners and their attitudes, local resources and legislative constraints. Furthermore, the study goes on to insist on the practical and long-term economic benefits of refurbishment under the proper conditions and why this should be fully understood by the householders.

Keywords: Construction Process, Energy Efficiency, Refurbishment Activity, Retrofitting, Northern Cyprus.
1 Introduction
This research project is undertaken in the Turkish Republic of Northern Cyprus (T.R.N.C.). This research investigates the socio-political developments that have had an impact on the architecture and the urban planning process in this particular region. The study focuses on identifying refurbishment activities capable of diagnosing and detecting the underlying problems alongside the challenges offered by the mass housing estates design and planning in addition to identifying the cultural influences in the refurbishment process, which allow for the maximisation of expected energy savings. The United Nations (2007) reports that rapid construction activities are responsible for the consumption of approximately two-thirds of global energy demand in urban and suburban areas, and are therefore responsible for major changes in the built environment. The Intergovernmental Panel on Climate Change (2007) indicates that urbanisation has led to an increase in temperatures of 0.006 Celsius per decade since 1900 on the global land record and 0.002 Celsius on the global and ocean record. In the T.R.N.C. the increasing number of construction activities has had an impact on the environment which is included in future assessments of problems for the mass housing sector. At the same time, as a result of an increase in summer temperatures and a decrease in temperatures during winter months have brought changes in urban energy use. The Ministry of Environment and Natural Resources Department of Meteorology-T.R.N.C. (Cevre ve Dogal Kaynaklar Bakanligi Meteoroloji Dairesi Mudurlugu in Turkish) statistics (2015) shows that the average annual temperature was 17.2° C between 1960 and 1991 and this increased to 17.7° C between 1991 and 2007. These results show that the island is threatened by the climate change impact now affecting the whole planet but within the T.R.N.C.

The rapid construction during the ‘property boom’ years led to a revived interest in the property market. Ghosh and Aker (2006) state that the expectations of the Annan Plan and changing market conditions throughout the world is prominent evidence that people from countries like Russia, Turkey, Greece, the United Kingdom, and Germany citizens began to show significant interest in buying their ‘second homes’ in the T.R.N.C. The increasing energy demand by the residential sector was felt mainly through rapid construction activities and a renewed concentration on economic improvement. In the T.R.N.C. the rapid and varied construction activity throughout the building sector resulted in economic growth. The State Planning Organisation-T.R.N.C. (Devlet Planlama Orgutu – K.K.T.C. in Turkish) (2008) statistics show that in the pre-construction period between 1997 and 2001, the GNP rate had an average of 1.8%. However, during the accelerated construction activity period between 2002 and 2006, this rate had jumped to 11% per annum. It should also be noted that during this same time the construction industry accounted for 8.1% of GNP in the T.R.N.C. (ibid). The results show how construction activity activated interest in construction projects. However, the situation led to unsustainable environmental problems, ecological constraints and energy issues.

The expected solutions of retrofit strategies should be effective, environmentally acceptable and feasible given the type of mass housing projects under review, with due regard for their location, the climatic conditions, within which they are undertaken, the socio economic standing of the house owners and their cultural assessments, local resources and legislative constraints. Furthermore, the study goes on to insist on the practical and long-term economic benefits of implementation of retrofit strategies under the selected research methodology (ethnographic study) and why this should be fully understood by the construction companies and householders. The subsequent sections in this paper are structured as follows; the paper will first discuss the background and justification of research, followed by the hypothesised relationships with regard to the
relevant literature. This is then continued with explanations on the methodology employed. Preliminary findings and discussions are given prior to the conclusion. Limitations and future research directions will also be discussed.

2 Literature Review

Cohen (2006) claims that in developing countries where urban growth and rapid urbanisation are occurring, un-controlled urban sprawl, poor land use planning and poorly-built housing estates has led to an impact on the current state of urbanisation and growth. Hence, regarding the T.R.N.C. case, changing the physical layout of the land together with un-planned land use are two major factors, which have resulted in architectural, urban and environmental devastation (Fig.1). For instance, the construction companies started their invasive developments in many cases without any official permission in the virgin shorelines, mountain regions and river beds and also before laying down any ground infrastructures such as roads, water, electricity. This situation has prevented efficient services being made available to the project sites for their completion; therefore, it has resulted in the abandonment of the mass housing estates by the construction companies.

Figure 1: Invasive and destructive mass housing development of the untouched natural habitat

In the T.R.N.C. urbanisation started in the 1980's because of the development in the economy which prompted a simultaneous demand in the mass housing sector. This led to rapid construction of the apartment blocks, detached, semi-detached and terraced houses being built randomly across the country in both urban and suburban areas. As a result of this exponential growth in the property market without any political agenda for controlling urban planning, infrastructure and the physical quality of the building and its adaptability to the local environmental climate. This led to poorly built houses without any initiative in the reduction of energy consumption from the buildings.

One of the main principal problems in evaluating the energy performance of the recently built housing stock is represented by the lack of current building regulations in the Town Planning Law 55/89 (Sehir Planlama Yasasi in Turkish). The current policies are adopted from similar regulations left over from the British administration. Ulucay (2013) states that the Town Planning Law no longer reflects the need and priorities of today’s development of urban and suburban areas. Because of the structure of the Town Planning Law 55/89, the problems of its existing poor urbanism approach in planning concerns are now an ongoing hindrance to the introduction and enforcement of proper architectural design tools and control mechanisms in the construction of buildings.
In the following research, which has been published previously, indicates that there is a lack of awareness in understanding the importance of energy use (Ulucay 2008). According to Ratti et al (2005), on strategy for putting this deficiency in understanding its right to explain the variance in energy performance in terms of the gap between design and construction process. Furthermore, Swan and Ugursal (2009) claims that the identification of the building diagnosis varies according to the age, size, type etc. of building. One prevailing opinion is therefore to transcend the benefits of simple energy efficiency and broaden it to a much wider perspective of energy performance in the current housing stock so as to begin accounting and combating the complex environmental processes that have already taken place.

In the T.R.N.C., the majority of the housing stock is built by private construction companies as stated in the previous paragraphs without any regulatory bodies to oversee and bring the industry into European Union standards to ensure that the housing stock is energy efficient. Here, particular attention is drawn to the existing legislative policies and its plans to promote at government level for the improvement of the energy efficiency of the recently built housing stock.

Another factor to be considered is the current economic downturn in the T.R.N.C., which means that the financial crisis has prevented construction companies and house owners from implementing energy-efficient technologies even though there is awareness of this factor. However, at the same time, the energy-efficient technologies offer an opportunity for highlighting the permanent benefits and the economic advantages of such improvements for the present time and the future. It is a given fact that a reduction in operating, maintenance and management costs, amongst others, are very convincing arguments for adopting retrofit strategies.

Recent studies indicate that the evolution of mass housing estates after the property boom in the T.R.N.C. brought massive changes in construction strategy, which now responds less favourably to occupants’ requirements and also their current social and economic aspects (Yorucu & Keles 2007; Mehmet & Yorucu 2008; Safaki 2011 and Yapicioglu & Wright 2014). In order to reverse the above man-made problems, Bourdic, Salat and Nowacki (2012) stress that an improvement in the physical quality of building stock is very directly related to such demands as a reduction in energy consumption and so a depletion in carbon-dioxide emissions. In this study, the one main point is for the construction companies to assess and adopt the necessary principles of retrofit strategies to the present mass housing stock in order to bring into effect the above stated matters.

The approach here is to look at buildings that have been built by private construction companies and have already been retrofitted by occupants in order to make the building more energy-efficient and adaptable to the local environment. This research is prompted by a recognition that the current planning policies have not been effective in taking into account the energy consumption of the recently built mass housing estates by the construction companies in the T.R.N.C. between 2003 and 2015 (The property boom occurred during this particular period because of the political changes in Cyprus). This research reveals that there is an urgent need for the governmental bodies to bring out new and effective polices for the mass housing sector to force the construction industry to apply the necessary retrofit strategies on a rapid and large-scale basis in order to reduce energy consumption.
3 Methodology

This research consists of interdisciplinary collaboration in the area where single disciplinary studies often takes place. In that sense there is communication and collaboration between research, design, and the implementation of policies and objectives for the construction industry. This research utilises a combination of qualitative research methods (ethnographic case study); semi-structured interviews and focus group discussions are all contained within this underlying approach.

Before undertaking these ethnographic study observations were carried out to include photographic documentation of housing estates, drawings, maps of cities and housing estates. The researcher applied ethnographic studies as follows:

1. Semi-structured interviews with construction company owners in order to understand the current condition of the construction industry and to understand the nature and benefits of implementing energy efficient technologies.
2. Semi-structured interviews with house owners to understand their willingness to participate in implementing retrofit strategies in their homes.
3. Focus group discussions with house owners to investigate why house owners intend to be involved in the refurbishment activity of the recently built mass housing estates.

These methodologies were set out to address the issues of the housing sector. Although, these research methods were tested in the T.R.N.C., at the same time it was designed to be applicable in the Republic of Cyprus with similar energy saving targets.

In addition, the research hypothesis is that energy saving actions such as adoption of retrofit strategies could contribute to the reduction of the negative environmental impacts of the un-controlled construction and refurbishment activities. This was mostly tested on mass housing estates, which have been recently built en-mass mainly by private construction companies.

This research includes some case studies, which considers different aspects of the housing estates such as location, characteristics, demographic structure of households and also information on the construction companies. The housing estates were chosen from 22 different projects in four different regions (coastal, inland, semi-mountainous and mountainous climatic zones) including urban and sub-urban areas; thus in order to have a good representation of the common drivers in the property market with different levels of required refurbishment activity and different samplings from different climatic regions.

It is further emphasised that the documentation of the field data has come from the identification of construction companies’ projects, their policies, their targets and the problems they encountered in both the design and building process. This goes some way in providing information on the current condition of the industry in a particular centre or region.

During the research process, the researcher contacted 15 construction companies. This research aim and targets were presented in order to get permission from these companies to examine their housing estate projects. For this purpose, 15 small and medium size architectural companies were identified in terms of their willingness to participate in the research process. These companies were key players, which have responded to the growing demand in the property market. Their structures and target groups showed variations within the location of the construction company and its projects.
Before starting to conduct semi-structured interviews with households, a questionnaire survey on ‘refurbishment activity and energy consumption patterns’ was prepared. This was partly to hear their views on how the retrofit strategies impacted on their own cultural assessment, but also to collect concrete examples of retrofitting experiences, which could be (anonymously) related to policy actors (institutions) to hear their responses. These data collection methods were looked at selected housing estate projects in terms of understanding typical energy consumption values and the effect of refurbishment activities. This method was also utilised in examining how occupants can play a key role during the implementation of the retrofit strategies. These interviews were intended to utilize information for each occupants’ demographic structure needs and intentions in its involvement of any aspect of the refurbishment process.

The people who were interviewed in order to participate in this study are all residents of single or multifamily owner occupied housing units. The participants were people who do not identify themselves as vulnerable. Each were given a questionnaire to complete and were also interviewed by the researcher. Furthermore, the economic, physical, social and cultural environment in which the study was guided was observed. This approach combines regular site visits to the same households for two seasons (summer and winter) for a report on the environmental impact of the built environment over a period of one year in different climatic locations. The researcher contacted households in different project sites to get permission to re-undertake the questionnaire survey in the following research period.

The interview guide was therefore pilot-tested. The objective of this methodology is to calibrate the policies of implementing the adaptation of retrofit strategies in order to illustrate a trend of refurbishment activity in the recently built mass housing estates. This method was used as background information for this study to fill a research gap and contribute to knowledge on implementing an adaptation of retrofit strategies.

The qualitative analysis software of NVivo was used to analyse the fieldwork data. The analysis was guided by a preliminary thematic analysis of the key concepts prompted on the interviews. The first three concepts consider the housing stock in terms of characteristics, quality and developments. The other three concepts deal with current polices and action plans to introduce control mechanisms for retrofitting projects. It should also be noted that the semi-structured interviews and focus group discussions were conducted with households only on certain selected buildings and so the findings of the study apply to the narrow field under investigation and was not broadened to include some form of generalised opinion.

Another contribution to the field is the general evaluation carried out on understanding energy consumption of recently built housing estates in the T.R.N.C. As this study shows, there is very little research available or undertaken in the academic world that targets ‘retrofit strategies’. This research concept will finally lead to assessing and generating new pathways of research and innovative design tools in the management of the mass housing renewal and urban development but at the same time involving the notion of a socio-cultural paradox. The aspect of this research is to understand how it’s best possible to integrate the application of energy efficiency technologies to the adaptability of the prototype retrofit scenario. It will include cross-cultural studies as a research concept to investigate the pattern interpretation of energy consumption use and retrofitting.
4 Analysis and Results

The study found that refurbishment activities are identified according to the degree to which the building components used by occupants with reference to three main indicators are interrelated; the age of the building, the construction material and its energy demand. Through these variations, it is possible to define a decay representing all major classes of buildings in the housing sector and to utilise the obsolescences as an indicator in an analysis of the buildings (ibid). This is one of the main reasons why different building typologies are widely investigated and considered strategic in the selected housing estates. For these reasons, an expected analysis is co-related to both these parameters concerning the construction material and its system, the obsolescent part of the building components, the energy efficient requirements and the interventions that come into play over time.

Another important fact is the role of the house owners’ requirements in the design process and how these may impact the construction process. Therefore, the great challenge is to create collaborative mechanisms whereby both the construction companies and the house owners may contribute and co-ordinate efforts in solving the energy problem. To reach this goal, the demographic structure of occupants and their behaviour is required. Each single household has to be convinced and assured of the reasonableness and the economic advantages that will accrue from investing in the improvement of building components concerning energy efficiency in and on their property.

Thus, in order to obtain reliable and effective results in terms of energy efficient improvements, it is important that the interventions are articulated by occupants in the housing sector, as they represent now the common problems of the new-built housing stock. In this research context, the selected housing projects are composed of heterogeneous buildings with different typologies and dimensions, and consequently with different built purposes applied.

Today primary needs have evolved according to the demographic structure of the occupants and their lifestyles, financial capacities and several different occupants’ profiles are identified naturally, these householders’ profiles differ according to which housing estate project is under discussion and what the construction companies’ targets were during the design process. However, it should also be remembered that house owners are now much more willing now to improve the physical conditions of their dwellings than they were in the past and the trend for refurbishment continues. Consequently, profiling occupants and their behaviour is a much more complex activity when it also takes into consideration the refurbishment habits of the occupants.

The construction systems and materials are common nominators in the selected buildings and are strictly connected with the choice of construction companies’ progress at the time. Therefore, the materiality of buildings is a significant indicator not only of its level of physical obsolescence, but also the rapid construction demand linked to implement poorly built materials at that time.

Table 1 shows the several differences occur among apartments, terraced houses, semi-detached and detached buildings due to typology, built-form, distribution and construction systems. The common factor is generally that the housing stock after the great expectations raised by the Annan Plan was not designed to meet today’s energy efficient standards especially concerning the control of indoor comfort conditions (heating and cooling) and the thermal losses due to poorly-built construction material choices. This means that offering adaptation of retrofit packages for improving energy efficiency in the
housing sector would not only bring a relevant reduction in energy consumption in the selected housing estates, but also that households can be strongly involved in reducing their energy costs.

| Table 1: The structure for identifying the problem of the selected building typologies |
|-----------------------------------------------|-------------------------------|----------------|-----------------------------------|-----------------------------------------------|
| **House Typology** | **Target Group** | **Hazard** | **Exposure** | **Location of the housing estates** |
| Detached house | Upper-middle income/ high income | Overcooling demand in summer time | Non-control mechanisms in the building regulations and codes | The built-purposes |
| Semi-detached house | Upper-middle income/middle income | Non-central structure to regulate construction companies under the umbrella of 'energy-efficiency' thinking | Housing typology | Construction typologies and elements |
| Terraced House | Middle income/ lower-middle income | | | |
| Apartment | Upper middle income/middle income/ low income | Non-regulations to control occupants activities on the refurbishment process | Refurbishment activities | |

In addition, the study also revealed that the changes of building components as articulated by occupants is on the increase. Even though some of the buildings have undergone major renovation, the addition of more spaces and the covering of terrace areas account for a high percentage of the renovation activity. Hence, the quality profile of this new-built housing stock changes gradually and only the construction process and renovations differ substantially from the housing stock.

Subsequently, it is quite hard to have a reliable forecast of the renovation trends without having a control mechanism and adaptation packages developed through an investigation of the selected buildings. At this stage, the preliminary findings show that identification of the diagnosis in selected buildings can be useful for understanding what main changes occupants are expecting in the housing sector, and for further investigating their requirements from the construction companies and their involvement in the decision-making process.

Moreover, the study found that the occupant's refurbishment trends affect not only the energy performance of buildings but also increases carbon-dioxide emissions in the environment. It is also worth commenting that the impact of the construction activity has produced further problems in the housing sector and this contributes to making an investigation of the potential adaptation packages much more complex. To compensate for this, a useful starting point could be identified as the diagnosis of buildings in the selected housing estates. What seems to be clear is that the physical quality of the buildings, the demographic structure of households and the quality of refurbishment activity is perceived as inappropriate in meeting the emerging demand of the housing sector.
5 Discussion

In this case study approach, 70 buildings are analysed and three key components of energy consumption are calculated in accordance with the contribution they make to an increase in energy demand. The key components derived from this case study approach are as follows:

- Building design performance (e.g. shape, envelope area)
- Efficiency of construction systems (e.g. age of boiler)
- Behaviour of occupants

In these selected housing estates, three main requirements have been associated with refurbishment trends.

The first one deals with the covering of terrace spaces in the detached and semi-detached buildings and balconies in the apartments and terraced houses and adding more room spaces as a whole (which is strictly related to the demographic structure of the occupants) in order to obtain two different kinds of result. First adaptable spaces allow for the extension of the living room, dining area and entry lobby of the buildings according to changes in the lifestyles of occupants. Second, it allows some spaces to be widened and given a more specialised function such as, more ample living spaces for a family or a room. This could be achieved by extending the spatial layout of the existing building. These kinds of interventions are generally integrated to the on-going changes of users’ profiles and to the trends of refurbishment activities and do not belong to concerns about reducing energy consumption demand but rather to the idea of improving the quality of living conditions.

The second refurbishment activity involves a general improvement of the dwelling and also of the building as a whole in terms of the replacement of kitchen units or bathrooms, roof insulation, installation of double-glazing windows and addition of shading panels (pergolas) directly to the outside of the building. Most of these activities are an expression of trends of informed high-quality interventions. Therefore, the problem is related to understanding the benefits of ‘energy-efficiency’ during the refurbishment process in order to meet the requirements of building standards. In most cases the refurbishment activity is perceived by the occupants not only as improving the quality of living conditions but also as a real opportunity to reduce energy consumption in the residential sector.

The third refurbishment activity deals with access to fresh water supply, the recycling of rain water and grey water and the connection to the grid which varies depending on the location of each housing estates. Nevertheless, these activities to improve the infrastructure of the buildings may have relevant effect in terms of the utilisation level of the housing estates. At the same time, many buildings are being fitted with solar panels.

It has also to be said that the most common refurbishment activity is the addition of new volumes adjacent to the existing building or open terrace areas on both the ground and first floors. These often unintentionally lead to increase in energy consumption of the buildings. Consequently, the changes on the current market conditions after the Annan Plan lead to the housing sector to becoming aware of the necessary EU objectives in the design process as regards to energy efficiency and also in defining the construction process and its impacts on the built environment.
6 Conclusions, Limitations and Future Research Direction

From the findings of the study, it can be concluded that the original contribution of this research lies in adoption of the retrofit strategies that systematically integrates energy efficiency standards in order to improve conditions within the housing sector under the combined influence of three variables namely the construction activities, occupants' behaviour and the energy consumption of buildings. In summary, this study process investigation analyses the pattern interpretation of the occupants' behaviour and their cultural assessment embedded energy performance of buildings during the implementation of retrofit strategies. In this context, no existing research was identified applying energy efficiency standards of retrofitting to any types of buildings, whether recently built mass housing estate projects or otherwise.

The results of the research will contribute to facilitate private construction companies that aim to support retrofit strategies by providing them with new guidelines and policies together with the necessary data about the implementations needed for the improvement of the housing sector in the T.R.N.C.

This research will enable households to become involved in the process of identifying the applicable retrofit scenarios, to improve living conditions and achieve minimum energy efficiency consumption of buildings. This research will provide the context with the knowledge to realise the main goals: the identification of possible future instruments and incentives that are needed to overcome the weakness in current legislation and so bring about a more energy efficiency housing sector.

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CASE STUDIES OF THE EFFECTIVENESS OF 4D BUILDING PERFORMANCE VISUALISATION

Panagiotis Patlakas¹, Georgios Koronaios², Rokia Raslan³ & Hasim Altan⁴

¹ CEBE, Birmingham City University, UK, panagiotis.patlakas@bcu.ac.uk
² Mendick Waring Ltd, London, UK, geo-arch@hotmail.com
³ UCL IEDE, University College London, UK, r.raslan@ucl.ac.uk
⁴ Department of Architectural Engineering, University of Sharjah, Sharjah, UAE, haltan@sharjah.ac.ae

Abstract: The performance gap between simulation and reality has been identified as a major challenge to achieving sustainability in the Built Environment. While Post-Occupancy Evaluation (POE) surveys are an integral part of better understanding building performance, and thus addressing this issue, the importance of POE remains relatively unacknowledged within the wider Built Environment community. A possible reason that has been highlighted is that POE survey data is not easily understood and utilisable by non-expert stakeholders, including designers. A potential method by which to address this is visualisation, whose benefits in communicating big datasets are well-established. This paper presents two case studies where EnViz, a prototype software application developed for research purposes, was utilised and its effectiveness tested via a range of analysis tasks. Both case studies refer to buildings in central London, and included data collected from POE studies as part of bigger projects. In the first case study, the effectiveness of the application compared to standard tables and graphs was measured via a web survey of 100 participants. In the second case study, a group of 10 participants undertook a range of tasks in order to evaluate how EnViz, and 3D/4D visualisation more generally, allowed them to comprehend POE data and thus influence their decision-making when it comes to applying environmental design fundamentals. The results are discussed and compared with those of previous work that utilised variations of the methods presented here. The paper concludes by presenting the lessons drawn from the five-year period of EnViz, emphasizing the potential of environmental visualisation for decision support in environmental design and engineering for the built environment, and suggests directions for future development.

Keywords: Post-occupancy evaluation, 4D Visualisation, performance gap
1 Introduction

1.1 Sustainability and the performance gap
Sustainability and climate change have arguably been two of the core concerns of the scientific community over the last decades. Within the Built Environment, the issue has moved from a topic of mostly academic interest in the 1960s to a fundamental concern in design practice. The importance of buildings in achieving global sustainability has also now been recognised by the United Nations (Lucon et al, 2014). A wide number of support actions, including educational drives, subsidies, and others, have been offered at a local, state, or international level to support sustainability in buildings in its various guises. Despite the considerable aforementioned interest and engagement, the desired outcomes have as of yet remained partially elusive.

Contemporary environmental design fundamentally follows processes similar to that adopted in other engineering disciplines: a suggested design is modelled digitally, and its environmental performance and impact is then simulated using appropriate software. A key aim of this process is that the simulation model is sufficiently accurate to provide decisive guidance to designers, and thus promote sustainable and climate-sensitive designs over ones that are less so, while remaining within the client’s budget.

In the past two decades, technological advances and widespread adoption of computing has resulted in a range of software packages that aspire to move the field of building simulation and evaluation from academia into design practice. However, when designs relying on such software were built and their real-world performance was tested, they were found to significantly under-perform when compared to the predicted (simulated) performance. A decade ago the term “credibility gap” was first used to describe the difference between the expectations at the design stage and the energy use of a building post-occupancy (Bordass, 2004). Today, the phenomenon is considered widespread enough that this disparity, now more commonly referred to as the “performance gap”, is largely taken for granted (De Wilde, 2014).

1.2 The Importance of Post-Occupancy Evaluation
Post-Occupancy Evaluation (POE) is an all-encompassing term for surveys whose aim is to systematically monitor and evaluate the actual performance of a completed building or infrastructure work. POE surveys are categorised into two main types: psychological, where the occupants’ or users’ satisfaction is recorded, or physiological, where ‘hard’ data is measured and analysed. A major part of POE surveys focuses on environmental issues, measuring properties such as temperature, relative humidity, concentration of CO₂ particles, illuminance levels etc.

The aim of POE analysis is two-fold: firstly, an understanding of the performance of a building can assist owners, facility managers, users, and other building stakeholders in optimising their behaviour to achieve what can be considered ‘ideal’ environmental performance. Secondly, designers, engineers, and researchers can evaluate actual performance (as opposed to intended performance), and thus have a robust evidence base against which they can benchmark the accuracy of simulation processes and efficacy of designs.

This loop process of design – simulation – construction – monitoring – analysis is common in most fields of engineering design and both its theoretical importance and practical efficiency is largely considered to be routine in such fields. However, while ideal in theory,
this process is less easily applicable in environmentally-conscious and climate-sensitive architectural design. While researchers and environmental specialists are generally able to handle with the large amounts of data generated by modern measurement techniques, this is not necessarily the case for other stakeholders. Building owners, facilities managers, senior managers, and architectural designers are just some examples of stakeholders who may be less inclined to believe that monitoring data are easily communicable. This could therefore act as an extra barrier to implementing POE surveys more widely or, even when they are conducted, lessen the impact of their findings (Patlakas & Altan, 2012). Given that POE surveys play a fundamental part in sustainability-oriented research, it is self-evident that they need to be promoted and such barriers addressed when and where possible.

1.3 The EnViz software

EnViz (derived from ‘Environmental Visualisation’) was a prototype research-oriented software application, developed at Southampton Solent University between 2011 and 2013. Its main aim was to highlight and apply the well-established advantages of 4D visualisation (Ware, 2000) into the field of POE analysis. The completed software provides 4D visualisation of temperature and relative humidity POE data, in a 3D-model context. Multiple models can be handled at the same time, and relevant criteria, with a respective tolerance rate (e.g. ±2 °C), can be introduced within the visualisation. The application also includes the relevant CIBSE guidance for the UK (CIBSE, 2006).

The software has both been utilised in a range of test projects, and in a series of workshops to evaluate its efficacy compared to standard methods of analysis with non-expert users. The results from these studies have been documented extensively in previous work (Patlakas et al, 2014). Generally, the 4D visualisation was found to be a powerful tool for the communication of large volumes of data regarding the environmental conditions of buildings, allowing the understanding of such data more quickly and with greater accuracy than standard graph-based methods. In addition, EnViz users found it easier to compare between spaces and place a specific logger reading in the related building context.

This study aims to demonstrate two new case studies, where EnViz was applied to complement POE studies. These case studies aimed to compare design-stage simulation with POE data using 4D visualisation, measure the effectiveness of 4D visualisation in the decision-making process, and finally gauge the importance of visualisation in evaluating and addressing the performance gap.

2 COMPARING SIMULATION & POE DATA

2.1 Building Performance Simulation Software

Computer-based Building Performance Simulation (BPS) started in the research community in the 1960s and is now an integral part of typical design office practice (Zhou, 2013). A range of BPS software is available today, from specialist packages such as EnergyPlus and IES Virtual Environment, to in-built features in general-purpose packages as Autodesk Revit. Such packages typically offer a range of 2d and 3D visualisation options to communicate the results of the simulation, and it has been suggested that these options improve the effective use of modelling results in sustainable design (Jeong et al, 2013). While commercial simulation software packages are able to invest in provision of attractive visualisation capabilities, less emphasis has been placed on the provision of similar visualisation capabilities for POE data analysis. The first case study, has therefore aimed to address this shortcoming.
2.2 Case Study 1: Central House, University College London

Central House, located in Euston in central London, is a building originally leased and then bought by University College London (UCL). The building was recently refurbished to improve its spatial and environmental performance, however no POE had been previously undertaken to investigate its actual “base case” thermal performance beforehand.

For the purposes of this study, the 4th floor of Central House was monitored, utilising HOBO Onset U12-012 data loggers (Onset, 2015). A total of 20 loggers were internally placed in a range of space types including corridors, toilet and shower rooms, meeting rooms, cellular offices, and open plan offices as shown in Figures 1 and 2 (Sang, 2015). The monitoring took place between the 19th of June 2015 and ended on the 10th of July 2015 (21 days). While this is may not adequate for a comprehensive environmental study of the building (especially given the lack of cold-weather data), it was deemed satisfactory for the purposes of this study.

Figure 1: Central House 4th floor overview. The highlight indicates the area of the study (Sang, 2015)

Figure 2: Logger placement. Red dots indicate internal loggers, orange dots loggers near air conditioning units, and blue dots indicate external loggers. (Sang, 2015)
A thermal simulation study of the building was also undertaken for the same period (Sang, 2015) using IES-VS 2014 based on as-designed drawings and some observation-based assumptions by the author. The simulation included the adjacent buildings, as these were deemed to have a significant influence on the indoor environment of the monitored spaces (Figure 3).

The simulation and POE data was input into EnViz to provide a direct comparison of the simulated and the actual performance of the space during the monitored period. Some examples of the resulting visualisations are shown in Figure 4.
2.3 Survey of effectiveness of visualisation

Following the completion of the simulation, monitoring, and visualisation process, an online survey was conducted to gauge the effectiveness of the 4D EnViz-based visualisation process in communicating the comparison between the simulation and POE data, as opposed to the current state-of-the-art (typically 2D graphs and tables). Respondents were provided with three representations of the simulation and POE results from a single day. These representations were:

(a) a table
(b) a 2D graph
(c) an EnViz visualisation

The questionnaire consisted of a total of 10 questions, 8 of which concentrated on the direct comparison of the three approaches. These are presented in Table 1.

<table>
<thead>
<tr>
<th>Q No.</th>
<th>Question Text</th>
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<tbody>
<tr>
<td>Q3</td>
<td>Which (of the figures) do you think shows the detailed temperature most clearly?</td>
</tr>
<tr>
<td>Q4</td>
<td>Which (of the figures) do you think shows the temperature change within a month most clearly?</td>
</tr>
<tr>
<td>Q5</td>
<td>Which (of the figures) do you think is the best for analysing the temperature difference within a month?</td>
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<tr>
<td>Q6</td>
<td>Which (of the figures) do you think is the most appropriate, in which data is presented to clients/occupants?</td>
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<td>Q7</td>
<td>Which (of the figures) do you think is the most interesting?</td>
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<td>Q8</td>
<td>Which (of the figures) do you prefer?</td>
</tr>
</tbody>
</table>

A total of 100 respondents took part on the online survey. A total of 38% of respondents declared having had been taught about indoor thermal comfort and/or more generally environmental design and engineering. This was in line with expectations, as a number of the building users were either graduate architects or students undertaking an MSc in Environmental Design & Engineering. The answers to Questions 3 to 8 are presented in Figure 5.

![Figure 5: Results to Questions 3 to 8 (Table 1), comparing visualisation options (Sang, 2015)](image)

It is interesting to note that, even though many participants found the graph more useful for comparing temperature changes, they overwhelmingly agreed that the 4D visualisation...
was the most interesting, and ideal for clients. In addition, the survey only presented data for a single day, i.e. a single day and a single graph. The advantages of 4D visualisation become much more significant when bigger datasets are introduced; previous work has suggested that users find much easier to understand bigger datasets with EnViz compared to data in spreadsheet form (Patlakas et al, 2014). As such it is reasonable to assume that if respondents were presented with bigger datasets, Questions 3 to 5 would have shown different trends.

It should be added that many respondents were critical not of the advantages of 4D visualisation as a principle, but of the specific EnViz implementation. A number of participants commented on the lack of features as compared to commercial-level software. Respondents also mentioned the comparable visualisation with features seen on computer games, which is typically the testing ground of the state-of-the-art in computer graphics.

The detailed results of the building simulation, POE monitoring and analysis, and the questionnaire survey can be found in Sang (2015).

3 MEASURING THE IMPORTANCE OF VISUALISATION IN THE DECISION-MAKING PROCESS

3.1 Case Study 2: 140 Hampstead Rd

The second case study was the (temporary) home of the Bartlett School of Architecture of UCL, Hampstead Rd 140. The building is a former warehouse that was refurbished to meet the needs of an educational studio/workshop space. The overall rectangular plan configuration includes a lower ground level, a ground level and two additional floors. For the purpose of this study, the examination of all floors was deemed unnecessary. Therefore, the first floor, where the studios of the students of architecture were located, was monitored and analysed (Figure 6).
The first floor is divided into two parts (east- and west-facing) which include studios divided by a series of lightweight partitions. These are separated by an row of enclosed seminar rooms and connected by two narrow corridors, which act as a barrier that slightly differentiate thermal conditions between the two zones depending on the time of day. The working and teaching spaces are serviced by a mechanical ventilation system, while the seminar rooms are fully-conditioned through a number of split air-conditioning units.

The observations made on the building were verified via two main categories of selective interviews, based on the time interviewees had spent working on that floor:

**Category A:** students or teachers that had spent a significant amount of time (over a year)

**Category B:** summer school students that had only occupied the space for two weeks.

The questions focused on their personal observations on the environmental conditions and occupancy habits/decisions based on their perception of thermal comfort, features of the space they occupied that affected their thermal comfort and environmental performance issues they could point out. Some key observations from the interviews are summarised in Table 2.

### Table 2: Key observations from interviews

<table>
<thead>
<tr>
<th>Topic</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working space preferences</td>
<td>• The majority preferred west-facing studios during the summer</td>
</tr>
<tr>
<td></td>
<td>• The majority prefers open to enclosed spaces</td>
</tr>
<tr>
<td>Thermal comfort perception</td>
<td>• All Category A participants stated the space had very bad thermal performance in both winter (too cold) and summer (too hot)</td>
</tr>
<tr>
<td></td>
<td>• Half of the Category B participants considered the space to be hot, while the rest was divided between warm and slightly warm</td>
</tr>
<tr>
<td></td>
<td>• 83.3% stated the space to be slightly dry, while only one individual considered the air to be just right</td>
</tr>
<tr>
<td></td>
<td>• 100% found the air to be rather still, affecting their perception over their thermal comfort in a negative way</td>
</tr>
<tr>
<td></td>
<td>• All Category A participants were taking action to improve their thermal comfort (using fans, moving to cooler places)</td>
</tr>
<tr>
<td>Layout and architectural elements</td>
<td>• 91.6% believed that the layout did not affect the thermal conditions in a negative way.</td>
</tr>
<tr>
<td></td>
<td>• The majority was unhappy with the windows as they were not openable.</td>
</tr>
<tr>
<td></td>
<td>• Lack of shading device enhanced overheating.</td>
</tr>
<tr>
<td>Mechanical systems and accessibility</td>
<td>• 33% of Category A participants claimed they had control over the cooling systems</td>
</tr>
<tr>
<td></td>
<td>• Category B participants were unaware of any existing cooling systems</td>
</tr>
<tr>
<td></td>
<td>• None of the interviewees believed that the systems installed were adequate for the needs of the entire floor.</td>
</tr>
<tr>
<td>Feedback to facilities managers</td>
<td>• Official and unofficial complaints made by full time students and teachers, focusing on lack of adequate cooling and accessibility of controls and windows</td>
</tr>
</tbody>
</table>

Following the interviews, a POE survey was conducted to compare reported perceptions with actual building performance. The monitored period was between the 17th and the 23rd of October 2015. Dry-bulb temperature and relative humidity were measured, with a data collection frequency of 10 minutes which resulted in a total of more than 1000
measurements. The data loggers were the same as the ones mentioned in section 2.2 of this paper. The types of spaces monitored are provided in Table 3.

<table>
<thead>
<tr>
<th>no.</th>
<th>Space type</th>
<th>Space characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Seminar room</td>
<td>Air Conditioned (cool)</td>
</tr>
<tr>
<td>2</td>
<td>Shared Studio West</td>
<td>West (heats up later)</td>
</tr>
<tr>
<td>3</td>
<td>Studios 12 to 16</td>
<td>West (heats up later)</td>
</tr>
<tr>
<td>4</td>
<td>Studio 17</td>
<td>Close to Plant-Room (warm)</td>
</tr>
<tr>
<td>5</td>
<td>Studios 19 to 24</td>
<td>East (heats up earlier)</td>
</tr>
<tr>
<td>6</td>
<td>Studios 18 and 22</td>
<td>East (heats up earlier)</td>
</tr>
</tbody>
</table>

The POE data were then imported into EnViz, and a range of 3D (static) and 4D (dynamic) visualisations were produced. These were then employed in a series of tasks to measure the effectiveness of the 4D visualisations in decision-making.

3.2 Decision-making Study

For this study, a group of 11 participants with specialist knowledge (prior knowledge of environmental design principles) were chosen, it should be noted that many of the individuals were not familiar with the case study building and none with EnViz. The study consisted of three tasks of increasing complexity, where participants were required to make estimates and take decisions based on EnViz-generated visualisations.

3.2.1 Task 1

For the first task, participants were asked to decide on whether they would take actions to improve the thermal comfort of some spaces, through the evaluation of a specific 3D visualisation (time snapshot) and estimation of temperatures and RH values in each monitored space. A sample screenshot of the visualisation is illustrated in Figure 7.

![Figure 7: Temperature (left) and RH (right) snapshot for Task 1](image)

For the seminar room all participants stated that they would take no action, while for Studio 17, 10 out of 11 stated that they would relocate, and specifically to the seminar room. For the other spaces, the most frequently stated actions were to readjust clothing and open windows, in order to regulate temperature and increase RH as the humidity was perceived by the participants as significantly lower than it actually was.

It is interesting that participants who were not familiar with the case study showed preference in interacting with the environment by using architectural elements (such as doors and windows) and not mechanical systems. That could be an indication that openable windows should be considered. In addition, it seemed that reading the colour scale of temperature was much more successful and the decisions were instantly made. On the contrary, RH was much harder to identify and comprehend. Thus colour scaling was very important in the comprehension of the visualisation, as a wider RH colour scale
one, was harder to read and identify accurately. The detailed results are provided in Table 4.

<table>
<thead>
<tr>
<th>Action</th>
<th>Seminar room</th>
<th>Shared Studio</th>
<th>Studios 12 to 16</th>
<th>Studio 17</th>
<th>Studios 19 to 24</th>
<th>Studios 18 and 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relocate</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Adjust Clothes</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Open Windows</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

3.2.2 Task 2

The second task attempted to gauge to what extent, the interaction with the software could lead to reasonable assumptions on actual building performance. Participants were presented with a 4D (dynamic) visualisation of the monitored floor for the period between the 24th of July 2015, at 00:00 and the 25th of July 2015, at 15:20. Following this a range of descriptions (such as “Air conditioned”, “West facing” etc) were presented in a random order. Participants were then tasked with the identification of the description that corresponded to each floor, by tracking the colour changes in the visualisation.

The success ratio for this task was 100%, which suggests that the tracking feature showing changes in the colour scale in multiple rooms provides a comparative tool that is both comprehensive and intuitive.

3.2.3 Task 3

For the third and final task, participants were asked to take part in a “gamified” decision-making process. The particular rules of the game were developed by the authors and can be found in detail in previous work (Patlakas et al, 2015). In summary, participants were provided with the monitored spaces, some of which failed to fall within the required thermal comfort criteria for some periods of time. They were given a limited budget, appropriately selected so it could not cover all areas, and were then asked to choose which ones they would ‘fix’ to meet required criteria. A further elaboration was set up, allowing participants to fix either the temperature or the relative humidity aspects in a room. To support their decision-making process, they were provided with EnViz 4D visualisations. Through using the software, they had to track the changes in the colouring of the rooms, estimate their failure rates, and thus prioritize the most important spaces to “fix”. Participants performance (i.e. how accurate their decisions were) intended to provide an insight into how accurate conclusions drawn from the 4D visualisation were. The game environment is shown in Figure 8.

![Figure 8: Decision-making task 3 environment](image)

The actual failure rates of each space, derived from analysis of the POE data, is presented in Table 4.
Table 4: Failure rates of monitored spaces

<table>
<thead>
<tr>
<th>Space</th>
<th>Overall Failure Ratio</th>
<th>Failure Ratio (T)</th>
<th>Failure Ratio (RH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar room</td>
<td>5%</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>Shared Studio</td>
<td>69%</td>
<td>48%</td>
<td>65%</td>
</tr>
<tr>
<td>Studios 12 to 16</td>
<td>62%</td>
<td>59%</td>
<td>45%</td>
</tr>
<tr>
<td>Studio 17</td>
<td>81%</td>
<td>81%</td>
<td>37%</td>
</tr>
<tr>
<td>Studios 19 to 24</td>
<td>66%</td>
<td>62%</td>
<td>35%</td>
</tr>
<tr>
<td>Studios 18 and 22</td>
<td>48%</td>
<td>46%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Table 5 shows the decisions taken by the participants. Specifically, it shows the number of participants that chose to invest in fixing temperature issues (T) and relative humidity (RH) issues for each space, thus indicating they found that space problematic.

Table 5: Participants’ decisions

<table>
<thead>
<tr>
<th>Space</th>
<th>Fixed T</th>
<th>Fixed RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar room</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Shared Studio</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Studios 12 to 16</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Studio 17</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Studios 19 to 24</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Studios 18 and 22</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

It is clear that through EnViz, the apparent overheating issue in studio 17 and the RH issues in the shared studio were identified and fixed by the participants. The space that was chosen to be fixed the most was Studio 17 (10 T fixes and 4 RH fixes), with the shared studio following with 12 fixes, 10 of which was focused on RH. The optimum solution was not achieved in any of the cases. However, it was clear that certain participant decisions derived directly from their use of the software. For example, there was a 100% tendency in fixing the temperature of room 4 and the RH of room 2.

The difference in the distribution between T and RH priorities by the participants, indicated that isolated examination of each of the factors (T and RH), was not very effective providing clarity as to which rooms suffered the most. Namely, it appeared that participants misidentified spaces as failing critically with regard to humidity, when this might not have been the case. However, it is likely that this is due to lack of familiarity with the software and/or the respective colour map and thus could be easily addressed (all participants were EnViz novices).

None of the participants exceeded the budget, but 40% decided not to spend all of it. This suggests that the decision making process was driven initially by apparent failures in the two rooms mentioned above, and the rest by the amount of money left and the possible combinations of fixing the rest without exceeding the budget, and not by the actual needs of the spaces. The full study, together with an analytic documentation of the POE measurements can be found in Koronaios (2015).

4 Conclusions

The work presented here concludes a five-year project in which a prototype software application for the 3D and 4D visualisation of POE data was developed and then tested extensively in order to understand the extent to which visualisation can contribute to communicating the results of POE studies to a wide range of stakeholders, from designers to non-expert building users. The above case studies complement previous work by suggesting additional ways to measure the effectiveness, and their findings largely agree with previous efforts.

In summary, it appears that the conclusions reached in Patlakas et al (2014) hold, namely:
Visualisation can be a powerful tool for the communication of large volumes of data regarding the environmental conditions in buildings. Visualisation in a three-dimensional model context allows the understanding of building-related data more quickly and with greater accuracy compared to traditional graph-based methods. Time-based (four-dimensional) visualisation provides a better understanding of time-fluctuating data. A volumetric model of a building can be created with a minimal overhead in time and cost. Colour-mapping can be effective in communicating building-related data in a three-dimensional model context.

As in previous work, most of the weaknesses reported by users and survey participants do not focus on the principle of 4D visualisation, but on the inherent, mostly budgetary, limitations between a prototype app developed for research purposes, and commercial, corporate-level software.

Between the start of the EnViz project and today, various initiatives have focused on the visualisation of building data (although using distinctly different approaches). The continuing increase in computational power and ease of software development, together with increased web capacity point towards future developments such as real-time visualisation of building performance and automatic response of buildings to changes in climatic conditions. Simultaneously, the expansion of Building Information Modelling (BIM) means that POE data need to fit into the wider BIM context. In addition, the continuing collection of POE data means bigger and bigger datasets and therefore all the challenges associated with Big Data. Thus, development of suitable digital frameworks is required if the performance gap is to be addressed, and the sustainability agenda furthered.

Acknowledgements
The authors would like to acknowledge the work of Yeyang Sang, aspects of which are presented in Chapter 2 of this paper. The EnViz software development was led by Dr Darren Roberts.

References


Abstract: Burglary security for households has been an important discussion topic for societies for many generations. Law enforcers, policymakers, academics, politicians and industry practitioners all debate on the most effective means of securing homes. Although individual homeowners can determine how secure and sophisticated their home security systems may be, this is not always the case in many situations e.g. in the delivery of large scale house building. In contrast, designers and specifiers of large house building projects are responsible for the level of security of these new homes in the first instance. Some research have suggested that very simple approaches such as quality window locks, indoor lights, door locks and external lights (the WIDE approach) are sufficient in significantly reducing the possibility of burglary on households. The aim of this research is to highlight some current perceptions and practices of expert designers and specifiers in the large scale house building sector with regard to burglary security. This research uses in-depth qualitative data collected through semi-structured interviews of experienced designers and specifiers from one of the UK’s largest specialists in housing. Findings from this pilot study suggest that these experts consider many issues when making decisions on specifications. These include crime survey statistics of the location of new developments, financial ceiling of retail value of properties and the demographics of the potential tenants. More importantly, word of mouth plays an important role in how designers and specifiers understand the susceptibility of a given area to burglary. This paper encourages a pathway for additional open discussions between relevant stakeholders such as members of the Secured by Design (official police security initiative), large scale house builders, homeowners and landlords in order to further drive down the occurrences of burglaries.

Keywords: Burglary and security, housing, large scale house building, specification.
1 Introduction

Burglary in housing is not new and continues to gain traction the news e.g. the Guardian and the Spectator (see Hunt 2016; Nugent, 2016). Several approaches have been implemented to reduce such household burglaries. Numerous security devices including alarms have been known to help prevent domestic burglary (Tseloni et al, 2014). Although it is assumed that households are safer with more security devices fitted to the property, this is not necessarily the case (Tilley et al, 2015). In actuality, the addition of burglar alarms can prove to be counter-productive based on findings from Crime Survey for England and Wales (CSEW) (ibid: 2). Several research have been undertaken on burglary and security trends using national crime statistics (e.g. Tseloni and Thompson, 2015; Farell, 2015; Armitage and Monchuk, 2011). Most of these research have approached the issue from the angle of criminologists and while making use of data from the Office for National Statistics and CSEW. Design teams in the construction industry can play an important role in reducing these household burglary incidents (Armitage and Everson, 2003). This paper thus explores the role of design teams including specifiers in reducing burglary in new homes. The main aim is to highlight some current perceptions and practices of expert designers and specifiers in the large scale house building sector with regard to burglary security. Large scale housing projects in this study refers to projects conventionally perceived to be large and understandably may differ from construction context to another e.g. in the UK any project larger than 50 units is publicly considered to be a large scale housing project. The large scale house building sector is chosen for this project because mass customisation in such projects can give these designers and specifiers a good opportunity to determine the security systems to be implemented in an entirely new community. Although there is no widely agreed definition of social sustainability (see Buser and Koch, 2013; Colantonio and Dixon, 2011), it is believed that improving safety and security measures in projects and in residential areas in particular, using subtle or passive measures will add to social stability and perception of safety which in return will improve sustainability at social and community levels. Furthermore identifying effective burglary prevention measures would be extremely beneficial to organisations that undertake large scale projects yearly. Following modern innovative principles in construction and mass housing design such as standardisation, repetition and simplification (see Dinçer et al 2014: 270) findings from this study can inform researchers and practitioners alike on cost effective methods of burglary prevention.

As a pilot study, this paper forms part of a larger project that seeks to explore the entire South East of England in a deep qualitative study which will present recommendations for reducing household burglary. Literature review on the role of specifiers and designers in the construction process is presented next in order to highlight the need for putting them at the centre of this study. This is followed by an overview of the Secured by Design (SBD) concept which has played a pivotal role in burglary prevention for households in the UK. The research method and the findings from the empirical work are presented subsequently, and then finally the conclusions and recommendations for the future of the project.

2 TYPICAL ROLE OF SPECIFIERS

Construction specifiers identify the materials, components and skilled labour required to undertake a given project (Emmitt, 2006). Specifiers and designers often make majority of their crucial decisions during the conceptual design stage instead of the detailed design and specification phases (Cox, 1994 Willis and Willis, 1997). However, it is very beneficial when these processes are carried out simultaneously (Emmitt and Yeomans, 2001). This ensures that ideas of the specifications and designs stay relevant especially when
Conceptual designs are amended for reasons such as client needs, availability of components.

According to the Royal Institute of British Architects (RIBA), specification used to be principally the role of the architects. This notion has been eradicated in recent times due to the invaluable contributions offered by other experts involved in both the conceptual and construction phases of projects (Kalin et al, 2010). Osman (2016) outlines the need for including the different professionals in specification process:

- **Architects**: need comprehensive product information; product installation methodology; knowledgeable supplier personnel; rapid response to site problems; and quick and concise solutions to queries.
- **Building surveyors**: need comprehensive product information; easy and immediate advice and samples; knowledge of product installation methods; and rapid response to site problems.
- **Quantity surveyors**: need early indicative pricing; comprehensive product information; easy and immediate advice and samples; and knowledge of product installation methods.
- **Contractors**: look for rapid response to site problems; consistency of service; guaranteed delivery standards; access to immediate advice by telephone or email; warranties and guarantees.
- **House builders**: need rapid response to site problems; consistency of service; guaranteed delivery standards; access to immediate advice by telephone or email; and knowledge of product installation methods.

The various professionals involved in the design phase and construction phase need to have a clear understanding of the various building materials, components and finally, the installation methods. Furthermore, professionals that work on buildings during the operational phase also need to be included in specification decisions as they will take over once the buildings have been commissioned.

There are British Standard (BS) codes that cover the various aspects of construction specifications. The BS codes on specifications cover the UK and international standards relevant to the preparation of technical product specifications in accordance with geometrical product specifications (British Standards Institution, 2008). In a scheme devised by the Association of Chief Police Officers (ACPO) to enhance household security, standards were set for builders with regard physical security, surveillance, access/egress and management and maintenance (Armitage, 2004). This scheme is known as Secured by Design.

### 3 SECURED BY DESIGN (SBD)

SBD is a police initiative to guide and encourage those engaged within the specification, design and build of new homes, and those undertaking major or minor property refurbishment, to adopt crime prevention measures (SBD 2016: 5). The scheme was initiated in 1989 and has evolved over the years due to review and further development. Armitage and Monchuk (2011) have studied the development of the scheme from its inception to its first major revision and this is presented below:
Table 1: Changes in physical security standards for SBD (1989 – 1999) (Armitatge and Monchuk 2011: 322)

<table>
<thead>
<tr>
<th>Time period</th>
<th>Physical security standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>SBD was launched in 1989 with window and door requirements based upon ‘specification’, as there were no specific standards for such products at this time. The windows section of SBD was very basic, with a requirement only for windows to be lockable (with a key). Requirements for doors mirrored those within the National House Building Council security section.</td>
</tr>
<tr>
<td>1992</td>
<td>In 1992, a National Technical Committee for SBD was formed. Window and door standards were still specification-led at this stage.</td>
</tr>
<tr>
<td>Early 1990s</td>
<td>The first true ‘performance’-based standards (GGF 6.6: Specification for Improved Security, Part 1 Casement and Tilt and Turn Windows) was introduced in the early 1990s, however, this was not formally referenced as an SBD standard and only promoted to window manufacturers by a small number of Architectural Liaison Officers (ALO).</td>
</tr>
<tr>
<td>1994</td>
<td>PAS 011: 1994 was adopted as a ‘test’ standard for SBD windows by the majority of police forces, however, it was never formally written into SBD requirements.</td>
</tr>
<tr>
<td>1997</td>
<td>GGF 6.6.2: Specification for Improved Security – Single Handed Residential Doorsets – was published in 1997, however, again this never became a national SBD requirement, although it was utilised by some ALOs.</td>
</tr>
<tr>
<td>1999</td>
<td>The first major revision to SBD took place in 1999. This was the most significant change in terms of physical security as it signalled the end of specification-led door and window requirements and the introduction of performance-led requirements – PAS 24: 1999 and BS 7950: 1997. The introduction of these standards removed any subjectivity and ensured that a consistent level of security was being offered by manufacturers.</td>
</tr>
</tbody>
</table>

Since its commencement in 1989, the scheme has been amended and improved continually to improve household security. Although the scheme places great responsibility on ALOs, it was identified in section 2 that other professionals are also key in all specification decisions. The scheme also began by focusing on new projects and developments, current provisions cover refurbishment and retrofitting projects. There are three categories of awards given to developers under the SBD scheme namely; Gold, Silver and Bronze. The requirements for these awards range from door and window specifications to lighting of footpaths in the communal areas. Suppliers of various components of housebuilders may work in accordance to standards provided under the SBD scheme in order to ensure security. However, there are financial implications that arise from procuring components from suppliers and manufacturers with standard compliance (SBD, 2016).

For the scope of this study, there is focus on specific procurement considerations made by the various individuals involved in the decision making process of the design phase of projects.

4 RESEARCH METHOD

Using a qualitative approach, this research investigates the role of experts involved in the decision making process of security measures implemented in large scale house building organisations. Although collective ideas are incorporated when such decisions are made, it is imperative that some of the views of the individuals involved are explored. Previous research on burglary and household security have used quantitative approaches to help in the understanding of the statistics and trends of domestic burglary and theft (e.g. CSEW). This research is more concerned with the qualitative aspects of the decision making process. That is, the reasons that are paramount to decisions made about burglary prevention approaches in the design phase of the construction process especially in the case of large scale housing. Findings presented in this study focus on the perceptions of the individual participants and not the collective decisions made in their organisations.

Through purposive sampling technique, semi-structured interviews were conducted with four experienced individuals involved in the decision making process for one of the largest house building companies in the UK. The questions asked in the interviews revolved...
around issues such as their views on the localities where the housing projects are being carried out and what techniques they considered to be critical in burglary prevention. Interviews were recorded with digital audio recorders and field notes. Transcription was undertaken verbatim and analysed using themes that were identified the literature review and emergent concepts from the participants. The emergent concepts will also be informative in the future of the research as the research moves forward. As this paper presents on findings from the pilot phase of the overall research project, it is important to clarify that other data collection techniques including documentary analysis and non-participant observations of design team meetings will be incorporated in the final empirical phase of the study. That is, alternative research methods will be used to further explore the emerging themes. This will offer a holistic view on decision making processes with regard to burglary prevention strategies on large scale housing projects. The findings, analysis and discussion are presented next.

5 FINDINGS, ANALYSIS AND DISCUSSION

All four research participants had more than five years of experience in decision making roles with regard to specification on household burglary prevention. Their views and opinions are presented in this section.

5.1 Expert considerations

Although the participants had extensive knowledge and experience in measures to prevent burglary, they all discussed the importance of consulting with experts before making any decisions on security and burglary prevention.

“We contact people like the local police” (Participant A)

Participant A emphasised the need to contact local police before any decisions were made. He acknowledged that although police in general could provide valuable information, local police had more knowledge that would be relevant to particular area. He added that this ensures that they do not take any potential threats for granted as well as ensuring that they did not incur costs on high security modifications that would not be necessary. This is a pragmatic assessment of acquiring crucial information that results in cost effective choices. By acquiring components that are fit for the security and environment e.g. windows with burglar proof barriers in an area than is not known for this type of crime, the homebuyer would be incurring unnecessary costs.

Other experts that the participants contacted were the suppliers and manufacturers of components such as doors, windows, glass and locking mechanisms. It was found that the procurement method of these components was very competitive and for this reason, suppliers were constantly striving to improve the quality of their products. One of the participants stated that:

“I only consider manufacturers who work according to Secured by Design standards” (Participant B)

He added that there may be manufacturers that may provide more secure components but the lack of assurance of the quality made it an unacceptable consideration. He explained that many overseas companies have contacted them with the hope of supplying them with door and window locks for relatively cheaper prices but they could not accept these offers due to the difficulty of ascertaining the quality of the products.

On the same issue, Participant B stated:

“When the suppliers are working to a standard [Secured by Design] you are guaranteed that your clients [house buyers] will be safe” (Participant B)

Guaranteeing the future homeowners’ security from burglary is very important because the same construction principles are used for the numerous homes that will be built. Furthermore, building secure homes will encourage other potential home buyers to contact
them for their services. The firm that the participants worked for had been in the news previously for building very secure homes in the West Midlands regions. Thus, there was a reputation to be lived up to as well.

5.2 SBD and internal layouts of houses
Participant A attributed their firm’s success in burglary prevention to SBD choices. He explained that the use of SBD products made it extremely difficult for burglars that it deterred them from their intentions.

“I think the Secured by Design is excellent” (Participant A)

The other participants agreed that components manufactured under SBD compliance were very effective at burglary prevention. Although they already knew about the high standards of SBD, Participant C was pleasantly surprised when she saw it in action.

“About three years ago, I had a site in Nottingham. And prior to completion, somebody tried to break into that house. They tried to get in, they couldn’t. They tried to break the glass of the patio door which is secure glass so all it does is shatter. It breaks within the film that’s covering it. I was really impressed. I was sad that somebody tried to break into it, but I was glad that I had seen the prevention and how well it works” (Participant C)

Participant C’s reaction goes to show that although she believed in the quality of the patio door glass, she did not know how it actually worked. She knew they were manufactured to standard but had not seen it being tested. It is therefore fair to conclude that she had faith in the system although she had not seen it being tested before.

Participant D also described a new practice by some of their suppliers who were placing the SBD logo/seal on their products e.g. door handles and window panes. He explained that the SBD concept is now popular so a burglar may know about the quality of security in the household they intend to burglarise. Going by this idea, if the would-be-burglar described by Participant C had seen an SBD symbol on the patio door, he would have retreated.

With regard to internal layout, Participant B explained that it was important that back doors of houses should not have see-through glass panes. Furthermore, they should have removable key locks on the inside because he believed if burglars saw it, they would be tempted to smash the window with the hope of sliding their hand through the open space and opening the door from behind.

Another internal arrangement that Participant C believed was very useful was using windows that did not open fully unless a mechanism is triggered from the inside. She explained that when households open their windows for ventilation, they do not have to worry about burglars opening them wider and jumping through. In other words, the space left when the window is open will be too small for a burglar to enter unless it has been opened fully – which can only be done from the inside.

Lights are placed in the front and back of the houses not only to lighten the area for sight but also as a burglary prevention technique. Participant A stated that burglars tend to stay away from well-lit areas at the fear of getting caught or identified. It was also found that it was common practice that their firm placed streetlights around the newly developed neighbourhoods to further prevent burglary. Tseloni and Thompson (2015) also found in their study that indoor and outdoor lights in addition to door and window locks were very important in burglary prevention.

5.3 Social unawareness
House buyers are usually not aware the security conditions of their new areas. According to Participant B, the house buyers tend to assume that all their neighbours are young
professionals buying homes for the first time. However, most of the new developments their firm carries out are regeneration projects. That is, they transform existing communities by tearing down old structures and redeveloping the entire area. He explained that the new homeowners are complacent about the level of security in their communities and often do not pay much attention to their burglary prevention. He said it was typical for front and back doors of some houses to be left unlocked and even open ajar at times. Having unlocked household doors and leaving one’s property unsecured presents burglars with opportunities. This has been known to be one of the main issues that leads to household burglaries. Farrell (2015: 1) states that offenders choose to commit less crime when it becomes more difficult to do so.

As mentioned by the participants earlier, they tend to consult local police about the burglary issues in the surrounding communities before making specification decisions. However, this information may not be passed on to the house buyers because it is deemed irrelevant once the security measures have been put in place or simply because they do not want to alarm these new property owners. Nonetheless, the house buyers will be managing and operating the properties upon completion and as such, must be informed of any potential problems that could befall them including the possibility of being burglarised.

Before the completion of a given house, the customers are given a tour of their future properties. This tour is given by a construction manager who then discusses the progress and expectations with the client. At this stage, it would be beneficial if the client is made aware of any existing issues about burglary in the wider community.

“Don’t leave valuables on view through windows” (Participant C)

Participant C said she always advised the future home owners to keep valuables out of the site of burglars. She explained that keeping things in view would tempt and encourage burglars to try and break in.

5.4 Financial constraints and client choices

House buyers are given the opportunity to include additional features to their houses when they are being built. Although the main structures will not be altered, the firm in question offers them the choice to add extra components or alter some of the designs. The customers have the choice to include extra security features such as surveillance packages and burglar proof barriers. According to Participant B, the customers are not aware of what may be required or not so they usually ask them about the supposedly right choices to make. He explained that the modifications varied significantly. They could be a simple motion triggered light or a sophisticated surveillance and alarm package. Participant C said she often advised clients to make sure their doors and windows were locked when leaving the house instead of asking them to purchase the security devices and additional modifications to the properties.

The extra modifications do not come cheap and this has been found to be a major barrier for customers when making this choice. Participant B stated that the cost these modifications are usually too high for customers especially if they are buying the house with all their savings. He clarified that the modifications are not included in the mortgage and as such, the client would have to pay upfront. Tilley et al (2015) found the price of enhancing household security systems to be relatively expensive. If house buyers do not have extra funds to upgrade these security systems, they may then be forced to compromise their overall household security.
5.5 ‘Myths’ about alarms and surveillance systems
From an informed perspective, Participant C and Participant D were not convinced alarms and sophisticated surveillance systems were effective in burglary prevention. Participant D stated as follows: “Alarms do not keep burglary down”

He added that burglary was a crime of opportunity and the perpetrators look out for situations such as open doors and unlocked windows. He also clarified that he believed that burglars would still be stopped by the SBD door and window locks regardless of the provisions such as closed-circuit television (CCTV) and alarm systems. Participant C reiterated her story about the patio door glass pane that a burglar tried to break into. She added that the burglar would have made their way inside the property had it not been for the SBD standard glass panes. Tilley et al (2015) found that alarms did not reduce the rate of burglaries in households. On the contrary alarms have become associated with increased rather than decreased risk of burglary with entry (ibid: 1)

5.6 Extraordinary circumstances
Participant A and Participant B had previously worked on a house that had been burglarised in an unusual manner. A hole had been created into the wall by the burglar(s). However, they explained that this was such an extraordinary situation that even the police were baffled by the method of the crime. When probed further about what could be done about such as situation, they both stated that this would be considered an exceptional situation that could not have been prevented.
Participant B stated that: “Well if you’re such a professional burglar, you can break into anything”

He explained that the preventative measures were more effective for opportunity burglars and not determined criminals like those that carried out the act described.

6 Conclusions
This study has explored the views of four individuals involved in the decision making stages of specifications of large house building projects. Semi structured interviews were conducted in order to uncover the opinions of these experts when making decisions that help prevent household burglary. The most important consideration made by these individuals is the use of components built to the SBD standards. The participants also believed that occupants of the houses could prevent most of the burglaries simply by ensuring that their doors and windows are locked, especially when leaving their homes. Furthermore the new property owners struggle to spend more financially to pay extra for more sophisticated security systems. Some of the participants were of the strong impression that security alarms and CCTV systems were not as useful as advertised. As this is a pilot study, insight has been generated for future investigations. The future work is underway to further understand the burglary prevention from the construction and design perspectives. Future data collection will include observations of the interactions of specification meetings that are undertaken by the experts. In addition, a questionnaire survey will be conducted amongst designers and specifiers of different large house building companies will be conducted in order for a comparison between the various companies to be undertaken.

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Abstract: Brazil faces the challenge of delivering affordable sustainable homes and it is emerging as a major problem due to the housing shortage of 5.8 million units. In March 2009, Brazil launched a social housing support program called “My House, My Life” (MHML) and it was aimed at promoting the production of new housing units for low to middle-income families. However, the previous experience of housing developments completed under the MHML program shows that the cost-driven delivery approach is affecting the whole lifecycle cost, quality and performance of these homes. The lack of housing design customisability and the negligence of overall product quality of these homes delivered to date have drawn frequent criticisms. In response to the demand to meet the housing challenge, Zero Energy Mass Custom Home (ZEMCH) global practices were reviewed, considered partially as a means to improve the design customisability and the energy efficiency and environmental comfort of homes without sacrificing production efficiency, effectiveness and cost. This paper will scrutinise the ZEMCH design approach and the applicability to social housing development in Brazil through the authors’ ZEMCH Workshop experience in 2014, 2015 and 2016.

Keywords: ZEMCH Workshop, Design Code, Social Housing, Brazil
1 Introduction

Housing shortage has been one of the major and challenging problems in Brazil, estimated in 5.4 million units, especially for low-income families which represents the biggest part of this number (IPEA, 2013). The Brazilian government program “My house, my life” (MHML), launched in 2009, aimed at promoting the production and delivery of new housing units for low-income families (Lonardoni et al., 2013).

In three editions of the program, the Brazilian government invested more than 190 billion BRL (i.e. equivalent to 58.3 billion USD) for the delivery of 2,980,177 units throughout Brazilian territory (Amore, Shimbo, & Rufino, 2015). Divided into three different segments, according to the family income per month, the MHML program target to contract 60% of the houses for households with an income up to 1,600 BRL (491 USD), named segment one. The other 30% of houses targeted households with income wage up to 3,100 BRL (950.92 USD) and 10% for families from 3,100 to 5,000 BRL (950.92 USD to 1533 USD), corresponding to segment two and three, respectfully.

However, the segment one has not been an attractive niche for construction companies due to technical and budget constraints (CBIC, 2014). For this and other reasons, MHML has been focus of several criticisms (Lonardoni et al., 2013). In a recent study, Amore et al. (2015) stressed that the delivered houses do not even achieve the minimum quality level required by international standards. The high demand and short time for delivering these houses contributed substantially to this drop in quality. Inadequacy of houses layout and incompatibility with family sizes (Amore et al., 2015), high energy consumption (Andrade, Assis, & Pinheiro, 2010) and low level of sustainability (Kowaltowski et al., 2005) were also major problems faced by MHML delivered houses.

Therefore, there is a clear and fundamental flaw in the current design process for which the Zero Energy Mass Custom Homes (ZEMCH) approaches has been contributing to improve social housing developments in the Brazilian context.

1.1 Zero Energy Mass Custom Homes Approach

In response to emergent global warming issues and constant increase of energy prices, low-cost housing in Brazil needs to be planned responsibly to ensure a reduction in energy use. The mass custom design concept has been considered as a means of enhancing the level of design customisation to meet the users and buyers’ individual needs, desires and expectations for housing (Noguchi, 2003).

The ZEMCH delivery approach has been introduced to the Brazilian construction academia and industry since 2011 through several activities such as seminars, workshops, conferences, and university lectures. The ZEMCH Workshops have been run yearly in Brazil for three years in a row since 2014. Students, professors and industry representatives joined together to maximise the interdisciplinary R&D activities that aim to demonstrate how to design the future of low cost and energy social housing developments in Brazil. The ZEMCH Workshop 2014 was held in Londrina at the State University of Londrina (UEL). The second ZEMCH Workshop took place at the University of Sao Paulo (USP) in Sao Carlos (Chvatal et al., 2015). The third ZEMCH Workshop occurred in Curitiba at Federal University of Parana (UFPR).

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According to the Brazilian currency conversion to US dollars in 28/08/2016 (1BRL = 3.26USD)
This paper aims to scrutinise the ZEMCH design approach to social housing development from lessons learned in the ZEMCH Workshop 2014, 2015 and 2016 as a means to foster the development of socially, economically and environmentally sustainable homes.

2 Method

Coined as a research methodology by Kurt Lewin (1946), an action research aims to create new knowledge through a practical learning process based on actions as means to a personal or professional development in specific contexts (Koshy, 2005). It focuses on identifying a problem or issues that may be improved, planning a change, acting and observing the process and consequences, and then, reflecting the outcomes (Kemmis, McTaggart, & Nixon, 2014). According to O'Leary (2004:141), an action research may have many cycles (Figure 13), or cycles of research.

![Figure 13: O'Leary's cycles of research Source: Koshy (2005)](image)

This paper scrutinizes the ZEMCH Workshops 2014, 2015 and 2016 according to the action research method to critically evaluate and reflect on the workshop progress (Figure 2). It comprises three sequential cycles of research. The evaluation also highlights the strengths and weaknesses of the ZEMCH Workshop experiences and lessons learned from one year to another.

![Figure 14: The action research method for the evaluation of the ZEMCH Workshop 2014, 2015 and 2016](image)
2.1 The ZEMCH Workshop 2014, 2015 and 2016

In 2014, the first edition of ZEMCH workshop was run featured as a pilot project. This ZEMCH Network fundamental move aimed to enable academics and practitioners to think and conceive housing design as a means to deliver an integrated and more sustainable product. It comprised 1) theoretical background, 2) function analysis, 3) design development, 4) energy and environmental assessment, and mass customisation, and 5) final presentation. In this first edition, participants were all Brazilian academics (master and undergraduate students, and experienced professors and researchers) and practitioners from building companies and industry. The ZEMCH workshops 2015 and 2016 provided students from the University of Melbourne with opportunities to travel to Brazil, visit local social housing developments and attend joint lectures delivered by renowned Brazilian researchers, and experience a ZEMCH design development workshop.

Lessons learned from that first experience lead to a new structure for the ZEMCH Workshop 2015 and 2016, divided into three main stages: pre-workshop, workshop and post-workshop. The pre-workshop phase should focus on a teaching and learning period for the introduction of the ZEMCH design approach and social housing development in Brazil. The teaching period should provide a theoretical basis for the ZEMCH conceptual and technical knowledge. Also, the UK Code for Sustainable Homes (BRE, 2010) and energy and environmental analysis software training were included as part of the pre-teaching period.

The Workshop was an intensive 5-day of interdisciplinary collaborative activities for the ZEMCH design development. The workshop period was divided into five main phases: 1) theoretical background, 2) function analysis, 3) design development, 4) energy and environmental assessment, and mass customisation, and 5) final presentation. The workshop started at the day 1 with an introductory lecture about ZEMCH design approach, social housing production system and construction systems for social housing in Brazil. During the day 2, the ZEMCH participants visited a local social housing community delivered by the MHML Program. The function analysis system technique (FAST) and evaluation criteria scoring matrix were carried out after the site visit. FAST classifies and associates a broad range of functions of the product to assist decision making (Elias, 1998). Evaluation criteria scoring matrix categorizes the priorities of a product according to a weighting criteria given to product’s function (Dell’Isola, 1997).

The design development practical activities started at day 3 and day 4 of the workshop. Firstly, the students developed a design code for the Brazilian context based on their function analysis and FAST diagram results obtained on day 2. Secondly, the housing development and benchmark were introduced to the design process as a requirement. The concept of mass customisation (Noguchi & Hadjri, 2009) guided the development of different housing typologies. Finally, the energy and environmental performance of the developed design options was evaluated, comprising: energy and daylight analysis, energy consumption analysis and energy production. Hot2000, Ecotect software were used to assess and improve environmental and energy performance. At the day 5, each group delivered a design portfolio in one A0 size poster as their final result. The final results were presented to the lecturers, guests and other participants.

The post-workshop comprised the development and delivery of an individual project. The universities defined the content independently, format and deadline for submission of the individual presentations. Also, the students were independently evaluated by their respective lecturer/university.
The ZEMCH Workshop 2015 and 2016 were run in collaboration with School of Design at The University of Melbourne. Seven masters’ students participated at the ZEMCH Workshop 2015 and, in the next year, sixteen students joined the Workshop 2016. Table 1 summarizes the participants’ scenario in the ZEMCH workshop 2014, 2015 and 2016, their fields of knowledge and universities. The authors of this paper are members of the ZEMCH International network. The first author has collaborated with the ZEMCH activities as research collaborator of the ZEMCH Brazil group since 2013. She joined the ZEMCH Workshop 2014 as an apprentice participant, the ZEMCH Workshop 2015 as veteran participant to then contribute to the development of the ZEMCH Workshop 2015 e-book (Noguchi, Yokota, & Melo, 2015) and work as volunteer tutor in the ZEMCH Workshop 2016.

Table 1: ZEMCH Workshop participants profile in 2014, 2015 and 2016

<table>
<thead>
<tr>
<th>Year</th>
<th>Participants</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
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<td>19</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>0</td>
<td>7</td>
<td>16</td>
<td></td>
</tr>
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<td>Universities</td>
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<td>Unimelb, USP, UEL, UNICAMP and UEM</td>
<td>Unimelb, UFPR, USP, UEL, UFSC, UFRGS, UEM and UNICAMP</td>
<td></td>
</tr>
<tr>
<td>Construction Companies</td>
<td>Tecverde and LP Brazil</td>
<td>RPS Builder</td>
<td>Tecverde and Smart</td>
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</tbody>
</table>

3 Discussions

This section will critically evaluate and reflect on the ZEMCH Workshop 2014, 2015 and 2016 experiences and lessons learned.

3.1 ZEMCH Workshop 2014

The ZEMCH Workshop 2014 was led by Prof Masa Noguchi from The University of Melbourne (Unimelb), Prof Hasim Altam from British University in Dubai (BuID) and Prof Ercilia H. Hirota. The ZEMCH Workshop 2014 day 1 started with an introductory lecture regarding ZEMCH design approach, followed by joint lectures regarding sustainability in buildings, and architecture and social housing in the Brazilian context.

It was observed that the practitioners could easily understand the principles of ZEMCH design approach. The nineteen practitioners, with a diversity of background (undergraduate students, master students, professors, senior researchers, practitioners), were allocated to four different groups and worked together for the delivery of a ZEMCH house. The site selected for developing the project was located in the university campus. The groups analysed the site conditions and the function analysis system technique (FAST) and the evaluation criteria scoring matrix guided the design decisions of each group. The results of the function analysis showed a range of different function options for the design concept. For instance, some groups focused on energy efficiency and passive design, while others prioritised mass customisation. The priorities of the project were established, and a master plan and an initial concept designed according to the selected function.

A lecture regarding the use of environmental analysis software guided participants to use software tools, developing energy and environmental analysis of the project. Due to lack
of experience in the use of these tools, it was reasonably time-consuming to them to get used to the software tools. However, the groups developed different house typologies/options for their project to mass customise the houses and simulated the environmental and energy performance. Image 1 illustrates the site visit, function analysis development, design development and final presentation during the ZEMCH Workshop 2014.

Image 1: ZEMCH Workshop 2014 site visit, function analysis development, design development and final presentation

The four groups presented the results (Fig.3) to the lecturers, local practitioners from the construction industry and guest lecturers in the last day of the workshop. The workshop practitioners could reflect on ZEMCH approaches, think and conceive housing design as a means to deliver a more integrated and sustainable product for the MHML program. Not only the workshop practitioners but also the guests from industry pointed out some aspects which have not been addressed in the social housing design process practice in Brazil. Legal requirements, local regulations, materials availability and budget constraints were some of the points discussed. This is very interesting study.

Due to the current problems faced by social housing in Brazil and lack of encouragement to invest in sustainability, practitioners brought up the following question: “How to introduce the ZEMCH design approach to a cost-driven delivery of housing developments?” Undoubtedly, the ZEMCH Workshop 2014 instigated the practitioners to consider passive design strategies for increasing sustainability, as well as the use of free of charge software programmes to simulate energy and environmental performance for energy savings in a lifecycle perspective. The first experience provided significant insights for the planning of the ZEMCH Workshop 2015. The lectures evaluated students learning experience to then restructure the ZEMCH Workshop scope.

3.2 ZEMCH Workshop 2015

In 2015, the ZEMCH Workshop format changed for a course work discipline. This change, alongside the interaction between Australian and Brazilian students, leaded to the
inclusion of pre and post workshop periods in the scope of the workshop. The pre-workshop period was a pre-requisite for attending the ZEMCH Workshop 2015 and it aimed to introducing the ZEMCH design approach to the workshop participants. It consisted of three weeks lectures for Unimelb students and 1-day class for USP students.

A group of seven students from Unimelb participated in the ZEMCH Workshop 2015. They arrived in Brazil a few days before the workshop started and visited Londrina, Rio de Janeiro and Sao Paulo, to become familiar with the local context. Londrina hosted a pre-lecture at UEL and a site visit to Vista Bela residential, the major social housing project delivered by the MHML. Then, the students went to Rio de Janeiro and visited Rocinha slum, the largest slum in Brazil, and other iconic buildings in the city. Sao Paulo was the last stop and included a tour visit at Ibirapuera Park, Paulista Avenue and historical centre. The tour ended in Sao Carlos, where the ZEMCH Workshop 2015 was held at the University of Sao Paulo (USP).

Coordinated by Prof Masa Noguchi (Unimelb), and Prof Akemi Ino (USP), the workshop activities started with an introductory lecture regarding ZEMCH design approach, followed by joint lectures about the social housing in Brazil, MHML Program, and construction systems. The joint lectures were presented by local professors from USP (Chvatal et al., 2015). The nineteen participants were allocated into four groups and, then, visited the Abdelnur Residential, a social housing project development delivered by MHML, which was under construction. During the tour, construction systems and techniques, as well as materials, the houses layout and the urban plan were observed.

During the design development, the Function Analysis System Technique (FAST), design code development, and energy and environmental performance simulation provided students with the opportunity to optimise the decision making process due to a clear establishment of objectives in the early stage. The FAST and evaluation criteria scoring matrix were carried out according to participants’ perception of housing needs captured during the site visit. The function analysis guided the design decisions, corresponding to the evaluation criteria scoring matrix results of each group. The design code brainstorming phase took place before the master plan and design solutions development.

Each group worked with a particular construction system to develop their project: Light wood frame, structural masonry, cast-in-place concrete walls, or cross-laminated timber. Prior to the environmental analyses, different house typologies/options were designed to achieve mass customisation. The energy and environmental analysis of each layout ensured efficiency and effectiveness for the design options. The final results were presented to the lecturers and specials guests from the construction industry at the day 5, providing a rich and fruitful discussion between audience and presenters. The final results (Fig. 4) were evaluated by lecturers, construction industry and the students. Image 2 illustrates the ZEMCH Workshop 2015 activities including the site visit, function analysis development, design development and final presentation.
The post-workshop period was established as a prerequisite for the evaluation of the ZEMCH Workshop 2015 participants. Each student developed a final individual work after the workshop. The Brazilian students developed their individual presentation based on the ZEMCH Workshop design outputs. The students from Unimelb developed a research paper related to the Brazilian social housing context. The final individual presentations were assessed by USP and Unimelb lecturers independently, according to different methods.

The material produced during the workshop were exhibited at the Melbourne School of Design (MSD) and the e-book ‘Travelling Studio (TS) Brazil’ was launched, containing the achievements of the ZEMCH Workshop 2015.

Considerable improvements were observed from the ZEMCH Workshop 2014 to ZEMCH Workshop 2015. The introduction of the ZEMCH Workshop 2015 as a discipline as well as the collaboration between both USP and The University of Melbourne can be considered as a significant movement in this workshop. The introduction of a pre-teaching period prepared students for the 5-day workshop activities and the post-workshop allowed them to reflect and crystallise their understanding about the ZEMCH principles. Also, the establishment of multicultural and multidisciplinary groups enriched the discussions during the design development. For the first time, students from two different countries worked together to discuss ZEMCH design approach. Both perceptions and misconceptions were brought up by students during the brainstorming and the design development. A critical analysis of the discussions allowed students to think about more sustainable practices. Clearly, the optimisation of time and scope during the Workshop activities resulted in positive outcomes. The ZEMCH Workshop 2015 feedback from students and professors guided the planning for the ZEMCH Workshop 2016.

3.3 ZEMCH Workshop 2016

Similar to the previous year, the ZEMCH Workshop 2016 was introduced as a course work discipline for students from Brazilian Universities and the University of Melbourne. The pre-teaching period was a pre-requisite only for Unimelb students to attend the ZEMCH Workshop 2016. The pre-teaching period aimed at introducing the ZEMCH design approach and the Brazilian social housing context to Unimelb participants with lectures in Australia. The pre lecture's content followed the same structure as the previous year. The TS Brazil 2015 e-book well as the exhibition content were utilised as a reference for the workshop activities as. Also, online video tutorials for the use of environmental and energy analysis tools were available for the students. Therefore, the students could access the materials and develop background for the ZEMCH Workshop.
The Australian students arrived a few days earlier of the workshop in Brazil and had the opportunity to visit Rio de Janeiro, Foz do Iguassu and Curitiba. Rocinha slum was visited with the objective to provide students with a social experience beyond the classroom. The sense of community, service’s organization, local growth and development in the construction sector opened their mind to real issues. In Foz do Iguassu, the group visited Itaipu Binacional hydropower dam and Iguassu waterfalls before Curitiba, where professionals from the public agency COHAB-PR, responsible for promoting low-income housing projects in Parana State, explained their operation in the social housing context in Brazil.

The workshop period was held at the Federal University of Parana (UFPR) and coordinated by Prof Masa Noguchi (Unimelb) and Prof Aguinaldo Santos (UFPR). The ZEMCH Workshop 2016 activities started with a ZEMCH introductory and theoretical background lecture, followed by joint lectures concerning Brazilian perspective on Mass Customisation and a Brazilian perspective on ZEMCH principles.

The participants were allocated to 4 different groups. During the day 2, the students visited Tecverde Company, which delivers light wood frame houses for the MHML, and the Castanheiras social housing development where they spent a couple of hours to, then, continue their activities back at the University. A representative from Smart BuildingCompany delivered a lecture about the concepts of steel frame to the students. After that, regulation for performance in buildings and construction prerequisites in Brazil, function analysis system technique (FAST) and evaluation criteria scoring matrix were carried out.

The workshop day 3 and day 4 followed the same structure as the 2014 and 2015 workshops. During the day 3, the students used the evaluation criteria scoring matrix results to develop the project, design code development and master plan. The energy and environmental design assessment knowledge transfer took place and the students learned how to utilise Ecotect, Hot2000, RETScreen. Additionally, Fluxovento software was introduced in the ZEMCH Workshop 2016 adding cross-ventilation analysis to the scope of the workshop. The groups focused the day four on the mass customisation design implementation. At the day 5, the final results (Figure 5) were presented to the lecturers and specials guests from the construction industry, which evaluated their final results. Image 3 illustrates the ZEMCH introductory lecture, site visit, function analysis development and design development during the ZEMCH Workshop 2016.
Many improvements were observed in the ZEMCH Workshop 2016. Publications and video tutorials helped students to assimilate the ZEMCH design approach previous to the workshop period. A strong collaboration between industry and academia was crucial for the workshop success as the construction sector’s involvement from both public and private organizations provided more technical support for this workshop. The opportunity to visit companies and building site and discuss with highly qualified professionals helped students to come with innovative ideas for social housing. Moreover, the support of professors from many different universities provided students with an effective support for learning. The equivalent number of Australian and Brazilian participants provided awareness during the design brainstorming discussion due to variations in economic and social aspects in Brazil and Australia. Also, the different background among participants (e.g. engineers, architects, urban planners) had enriched the discussions during the design development.

The post-workshop period focused a final individual project development of 1) a research paper with a minimum of 5,000 words or 2) a design portfolio for Unimelb students. Five students had chosen option 1, while eleven students developed option 2. The final individual work outcomes were assessed forty days after the workshop. The individual works had a variety of outcome with a wide range of topics with focus on mass customisation such as mass personalisation, green design, affordable mass customised houses, edible garden, urban development for mass customised houses and energy and environmental efficiency. The Brazilian student’s evaluation was based on the final group presentation. Table 2 summarizes the ZEMCH Workshop activities during 2014, 2015 and 2016.
The ZEMCH Workshop scope shows significant improvement throughout the past three workshops. The ZEMCH Workshop 2014 focused on transferring the ZEMCH principles to Brazil as a pilot project. The ZEMCH design approach was innovative and unlike the typical design development process for the delivery of social housing. The first experience of an integrated design development between Australian and Brazilian students changed the dynamics of the activities in the ZEMCH Workshop 2015. The influence of knowledge transfer was as important as the theoretical aspects. The process of thinking and sharing ideas levelled up the final results. In 2016, the scope and experience optimised productivity during the 5-day workshop period, with a high level of involvement from both professors, students, staff and industry.
4 Conclusions

This paper intended to scrutinise the ZEMCH design approach to social housing development from lessons learned in the ZEMCH Workshop 2014, 2015 and 2016. Design customisability, energy efficiency and environmental comfort of homes guided the design process of the ZEMCH Workshops 2014, 2015 and 2016. The ZEMCH Workshop experience was critically evaluated and examined in three learning cycles. According to the findings, the ZEMCH Workshops had shown significant contribution to the social housing design process throughout the last three years. Local and production systems, technologies and materials were carefully studied during the workshop.

The workshop method improved along the three editions. The ZEMCH Workshop 2014 was tremendously important for the establishment of the subsequent workshops, spreading the ZEMCH design approach in Brazil, which provided new partnerships with local companies and some of the main public Brazilian universities. The ZEMCH Workshop 2015 was the first experience integrating local and overseas students. This multicultural and multidisciplinary approach for the Brazilian social housing problem led to a diversity of questions and new thoughts, and resulted in valuable outcomes for both the participants as well as for the Brazilian researchers and practitioners. The ZEMCH 2016 achievements can be considered in a aftermath of the past workshops efforts, counting with enormous support from different universities, lecturers, researchers and local companies. Clearly, there is a significant enhance from one year to another in terms of lectures content and extra support from the ZEMCH researches and publications. The lectures have been revised and new researches about ZEMCH design approach has been published since the first workshop, which can be easily accessed.

The ZEMCH efforts provided an extraordinary positive result not only regarding teaching, method and scope. The introduction of ZEMCH design approach to highly qualified professionals/students resulted in a positive thinking about sustainability that goes beyond the project and lessons learned in class. The visit to different places around Brazil provided the students with unique and enriching opportunity to better understand both, environmental and social issues, as well as problems related to economic polarization in Brazil, especially for the Australian students. Also, the international experience involving Brazilians and Australians contributed to their skills development. The ZEMCH Workshop provides an opportunity to different people, with different background, to join in teamwork for developing a social housing project, and build a pathway to develop social and environmental awareness as well as to think ‘outside-the-box’. Brazilian students provided local information to Australians whereas Australians could bring a different perspective regarding construction systems and techniques, which differs significantly in both countries. Another important factor that should be highlighted is that the understanding of cultural issues were better assimilated by the Australians students while in Brazil. Experiencing real life in low-income communities through a site visit as well having the opportunity to talk with local people made this experience more valuable for the design development.

Therefore, the introduction of the ZEMCH approach can be considered as a means to clearly consider best sustainable practices for the improvement of social housing developments without sacrificing production efficiency, effectiveness and cost. There are many opportunities to be considered for the continuous improvement of the next ZEMCH Workshops. Future research could further explore the development of learning metrics, and provide significant insight to maximize the quality of the students learning experience. It would be interesting to develop pre-workshop and post-workshop questionnaires to assess the students’ confidence in understanding ZEMCH design approach.
References


Abstract: Although they tend to be pursued as two distinct research domains today, Zero Energy Mass Custom Home (ZEMCH) and Green Target Costing (GTC) approaches may become integrated towards the possible contribution to the development of socially, economically and environmentally sustainable homes in Brazil and beyond. Since 2011, as a means to foster the development of sustainable homes, the ZEMCH delivery approach has been introduced to Brazilian construction industry and academia. GTC is a strategic cost management approach that enables stakeholders in various manufacturing sectors including the construction industry today to secure a targeted profit margin while increasing product values. This study first explores how GTC can be combined with the ZEMCH engineering design approach through the authors’ experience of the ZEMCH engineering design workshop held at the University of Sao Paulo in 2015. Second, it examines the effect of the ZEMCH engineering design and GTC integrated approaches on the development of social housing in Brazil.

Keywords: ZEMCH workshop, Social Housing, Sustainable Development, Green Target Costing, Energy Efficiency.
1 Introduction

Sustainable housing development is a major challenge in Brazil and it is experiencing a severe housing shortage of 5.4 million units, which 90% of the homes are aimed to accommodate low-income families (IBGE, 2012). Only 52.5% of Brazilian households have water supply, sewerage or septic tank, waste disposal and up to two residents per shared bedroom (IBGE, 2012). In 2009, the Brazilian government launched a program called Minha Casa, Minha Vida (My House, My Life), aiming to reduce the housing shortage. The program had delivered 3.4 million housing units over the last six years and it is still in progress. The lack of design customisability and overall product quality of these homes delivered to date is a frequent criticism (Ferreira, 2012; Cardoso, 2013). Recent studies highlight the energy inefficiency and thermal discomfort of these social houses occupied. These results to some extent reflect the absence of the contractors’ and designers’ attention to the post occupancy housing performance (Morais, 2013). Today, the housing delivery is driven mainly by reducing the construction costs rather than considering the whole lifecycle cost and performance that affect the users’ capacity for both buying and maintaining their new homes.

Since 2011, as a means to foster the developments of socially, economically and environmentally sustainable homes, the zero energy mass custom homes (ZEMCH) delivery approach has been introduced to Brazilian construction industry and academia through a number of the meetings, seminars, workshops and conferences, as well as university lectures in Brazil. For example, the ZEMCH 2014 International Conference was held at the State University of Londrina in 2014 and the University of São Paulo, São Carlos hosted the ZEMCH Workshop 2015 (Chvatal et al., 2015). The mass custom design concept has been considered as a means of enhancing the level of design customisation to meet the user/buyers’ individual needs, desires and expectations for housing to be purchased and the production efficiency that helps lower construction costs. In view of the recent 30% hike of energy costs in Brazil, the need for producing low/zero energy housing is growing. Social low-cost homes are no exception. Accordingly, the energy-efficient and environmental design needs to be applied to these homes so as to embrace the whole lifecycle cost and performance. In this sense, the concept of Green Target Costing (GTC) is part of a proactive vision in which the principles of Target Costing (TC) are integrated with environmental requirements. Therefore, the synergy between GTC and the ZEMCH engineering design approach to social housing developments in Brazil can be considered to be desirable.

2 Green Target Costing

Horváth and Berlin (2012) offer insight on integrating the costs of environmental requirements with TC. The authors divide GTC activities into six steps:

1. Identification and valuation of desired green specifications and functionality;
2. Evaluation of target selling price and of green price premium;
3. Adjustment of green profit margin and calculation of allowable costs;
4. Cost breakdown on green cost drivers;
5. Execution of green cost management measures;
As a result, a comprehensive product design approach is built, in which environmental costs and impacts are identified and improved, and customers’ requirements can be met along with environmental requirements and cost constraints.

The first step, the identification and valuation of desired green specifications and functionality, is specified from a customer’s viewpoint. In this sense, it is noted that customers are usually unaware of environmental requirements. Thus, companies implementing the specifications and product features based on a pull or push basis. In this case, "Pull" describes the implementation as a consequent of customer demands, and "Push" is the characteristics of innovative green products.

The second step, the evaluation of target selling price and of green price premium, is occurs through analysis of competitive market conditions and customer feedback. According to Horváth and Berlin (2012), while some studies, argue that customers are willing to pay for green premium cost; others point out that this price can only be realized under certain circumstances. Thus, if the client is not willing to pay more for sustainable attributes, the selling price is established based on existing sales price in the market.

The third step, the adjustment of green profit margin and calculation of allowable costs, as in the traditional process TC, for calculating allowable costs by deducting the target profit margin from the target price. However, in the case of green products the profit margin needs to be adjusted due to the high risk associated with this type of product. Risks include, among other things, the lack of common experience organizations are still experiencing the challenge of sustainability; and the risk linked to high probability of sustainable product to less successful than the traditional. Moreover, it is also necessary to consider the indirect costs. The costs imposed on the product life cycle are covered by the selling price, but only the direct costs are part of the TC. Indirect costs, such as administrative ones, make up a block and are provided with proportional cost targets, independent of the customer’s perceived value.

The fourth step, cost breakdown on green cost drivers. After establishing the allowable cost of the product, designers then determine the allowable cost for each component. Customers’ values are then translated into product characteristics, and consequently, assigned to product components. This process of assigning values to the product components is highly subjective and is usually performed by the quality function deployment (QFD). In the context of the GTC, this assessment of the designers is even more critical, because it is needed a knowledge of the environmental impacts related to each component.

The fifth step, execution of green cost management measures. This step consists of three actions:

1. Determining the standard costs of the components with due regard to the costs of greening those products;
2. Comparison of standard cost and the allowable cost for each component is made through a value control chart;
3. Analysis of the differences in order to improve the design of components and minimize the total cost without compromising the functionality and quality. The sixty step, green kaizen costing, or the continuous improvement process is an extension of traditional kaizen costing now concerned not only with the reduction of costs, but also environmental issues.

3 ZEMCH Approach
ZEMCH is an acronym of Zero Energy Mass Custom Home aiming to tackle issues arising in the delivery of socially, economically and environmentally sustainable built environments in developed and developing countries, which accommodate people with different socio-economic backgrounds that relate to ages and abilities.

4 Research Method
Case study was the research strategy adopted. The case study in this research can be classified as exploratory, since there is still little understanding of the phenomenon studied (YIN, 2003). The ZEMCH engineering design workshop held at the University of Sao Paulo was the unit of analysis. Data analysis focused on comparing the design techniques (e.g. function analysis and evaluation criteria scoring matrix) used in the workshop with the six green target costing steps.

5 ZEMCH WORKSHOP Description
The ZEMCH Workshop at the University of São Paulo was designed to transfer technical design knowledge required for the delivery of zero energy mass custom social homes in developing countries. The first day of the workshop included an introduction as part of the Theoretical Basis. The main subjects discussed were ZEMCH concept, Social housing production system in Brazil, and different construction systems for social housing in Brazil. The postgraduate students from University of Melbourne presented the Code for Sustainable Homes and the environmental simulation tools for the energy analysis were introduced. The second day was devoted to the Site and Function Analysis. The Site analysis was based on a site visit in São Carlos, as part of the Theoretical Basis. Students and tutors visited the Abdelnur Residential, with 1032 houses constructed with Cast-in-place concrete walls.

The function analysis was based on aspects observed during the site visit and the way of achieving the ZEMCH concepts adapted to the Brazilian reality. The students could observe some negative aspects, such as monotony of the implantation, same pattern of house units, long blocks, insufficient public infrastructure, few connections to the city, no commercial service, little interaction between residential lots and green area and no public transportation in the vicinity.

The function analysis was based on aspects observed during the site visit and the way of achieving the ZEMCH concepts adapted to the Brazilian reality. The Functional Analysis System Technique (FAST) creates a graphical representation to show the logical relationships between the functions of a project, product, process or service based on the questions “How” and “Why”. It enables participants to think about the problem objectively, identify both the scope of the project, by showing the logical relationships between functions, and all the required functions and verify if a proposed solution has achieved the design needs. It also enables the identification of unnecessary, duplicated or missing functions. The following questions should be approached for the creation of a FAST Diagram: “How can this function be obtained?”, “Why have you adopted this function?” and “What other functions should you adopt? The FAST Diagram was developed in two hours and according to aspects of social housing production observed by the students.
during the site visit, the ZEMCH concepts and some categories of sustainable design from the Code for Sustainable Homes.

The time devoted to the function analysis was enough for each group to brainstorm their ideas, structure the diagram, construct the evaluation criteria scoring matrix and present the results. During the brainstorming process, the tutors and assistants visited each group to encourage them and clarify doubts. The function analysis guided the students during the design stage and helped them to be more efficient during this process. After the FAST diagram creation, the most important criteria were established and punctuated according to levels of importance. This procedure was conducted with an evaluation criteria scoring matrix. Each evaluation criterion was compared to each other and punctuated. The scoring matrix was constructed according to the criteria indicated by the FAST diagram, with the following order of importance: 3-High; 2-Average; 1-Low. The total score and equivalent weight were calculated for each function. The next two days were dedicated to the design code development and energy analysis, and the students considered both the mass customization concepts and the main priorities of each group. They selected a construction system, developed a new master plan and designed solutions to achieve the ZEMCH concepts. The design development was based on the priorities established by the FAST Diagram and the scoring matrix. The energy analysis helped the students to achieve the best solutions with lower building energy consumptions through three programs, namely Ecotect, Hot 2000 and RetScreen.

The last day of the workshop included the Design Portfolio Development, with ZEMCH design finalization and presentation of the material developed during the workshop. Each group prepared a poster and an oral presentation on the ZEMCH proposed for São Carlos, according to theoretical basis input and function analysis exercises.

6 GTC combined with the ZEMCH engineering design approach

The GTC is included as a comprehensive approach in which the costs and environmental impacts are identified and improved throughout the process, and customer values are met with environmental requirements and cost constraints. Although the model has to focus on the development of manufacturing products, it can also be adapted for the construction industry.

The figure 3 summarizes a product development process applying the green target costing approach in the construction industry. It is based on Horváth and Berlin (2012), following the first five green target costing principles. The last step, the green kaizen costing, was not addressed in this study because the goal was explores how GTC can be combined with the ZEMCH engineering design approach during the design stages. In Figure 3 the
main steps of the green target costing approach are explicit. The first step is the identification of customer requirements, the key environmental impacts and the requirements to be met in the certification process (Figure 3, part 1, 2, 3, 4).

Following step two, the target selling price is determined through analysis of competitive market conditions and customer feedback (Figure 3, part 5). Then, the calculation of the target profit margin is the result of a long-term profit analysis, based on the return on sales. This calculation should also consider the risks associated (Figure 3, part 6, 7). Subsequently, the indirect costs are established and the allowable costs are calculated (Figure 3, part 8, 9).

The balance between costs and value delivery is performed on the basis of a value methodology (VM). VM in building construction is a broad concept that encompasses the process of improving value delivery to customers from initial conception, to the buildings in use and their operation (Kelly et al., 2004). In the present research the VM methodology was proposed to achieve value by reallocating costs to better assess the value delivery to end-users, without compromising initial project costs. Many existing techniques and tools can be applied to a problem solving VM exercise. In the present research the ZEMCH engineering design approach was incorporated through the adoption of the highlighted techniques (Figure 3, part 10, 11, 12). Function analysis, FAST diagram and scoring matrix are added to support decision making in a more focussed manner and to improve the results obtained with the implementation of the GTC. Based on this techniques and tools with the inclusion of cost parameters it is possible to obtained a graph known as Compare graph (Csillag, 1995). This graph makes it possible to perform a comparison of the value and cost of each product function (Figure 3, part 13).

Furthermore, a life cycle assessment is carried out to determine the standard environmental impacts and the allowable environmental impacts (Figure 3, part 14, 15). The life cycle assessment along with the certification systems is one of the most efficient methods to raise the performance level of the building.

In the step five, the standard costs of all components are determined and then compared to allowable component costs (Figure 3, part 17). The comparison of standard cost ratio and allowable cost ratio is realized through value control chart and an environmental chart (Figure 3, part 18, 19). As a result, it is possible to identify the areas with demand for action.

Lastly, the GTC approach suggest improve the component design with reference to the value index and the environmental index (Figure 3, part 20). The value index is the proportion between standard cost ratio and allowable cost ratio, while the environmental index is the proportion between standard environmental ratio and allowable environmental ratio.
Figure 3: GTC combined with the ZEMCH engineering design approach
7 The effect of the ZEMCH engineering design and GTC integrated approaches

In the original GTC approach the customer’s perceived value of product attributes is assigned to the components through the process of quality function deployment (QFD). QFD is a method used for the transfer of customer needs into product requirements and process. Your goal is to establish the quality of the project, ensure customer satisfaction, and make the split of the project goals in terms of quality assurance, to the production stage (Akao, 1996). In this research, we adopted the ZEMCH engineering design instead of a QFD process in order to reallocate costs and enable a better value delivery to end-users. For the design process of sustainable buildings the use of the function analysis, FAST diagram and scoring matrix show as the most viable tools to achieve the objectives of GTC.

Function analysis is an important manner to identify functions, classify them and associate their costs. The use of this technique in the context of the GTC approach it is an opportunity way to clarify what the users need, especially the green requirements. FAST diagram introduces a visual tool capable to obtain detailed information from different perspectives. The process usually made by a multidisciplinary group is a better way to simulate problem solving and make creative decision. For the GTC approach, this is a recommend tool because it facilitates the interaction of stakeholders in reaching consensus at a multidisciplinary work team. The scoring matrix provide the most important information according to the value parameters. This analysis aim to show the relative percentage obtained to meet the desired criterion. In the context of the GTC, this allowed designers to identify the green value attributes and incorporated into the analysis.

Moreover, rather than individual benefits of each of the tools and techniques described, it is possible via the obtained data comparing values and costs from the customer’s perspective. The compare method shows in a graph the cost distributions along with their respective functions. As a result, this analysis provided the identification of areas for improvement considering a ranking of desired values. In the graph, it is also possible to identify functions that focussed on cost reduction and functions with a value that could be increased.

The application of the this techniques and the COMPARE method in a project with cost constraints showed that improvements seeking a better assessment of the value for end users resulted from simple cost reallocation (RUIZ et al., 2014). For the GTC approach, the effect of the ZEMCH engineering design and the graph result of the data obtained are shown as a valuable tool to deliver more green value to the end user. In addition, the identification and comparison of costs and values contribute to a better assessment of project investment areas.

8 Conclusions

This paper contribute to the promotion of discussions on more efficient ways of developing social housing projects. The problems associated with the traditional practice of reducing costs in construction (e.g. lowering specifications and reducing quality) and the opportunity to integrate the ZEMCH approach with green target costing guided this research. In this sense, the green target costing is a promising approach to secure a targeted profit margin while increasing product values.

In this study, we aimed to show that concepts discussed in the ZEMCH Workshop and GTC can be applied to deliver more value to end-users according to their value perspective. Through a systematic evaluation of costs and their reallocation connected with the delivery of green value to end-users, the study believes that opportunities for
improvement social housing, without increasing costs and and adopting more sustainable measures.

The proposed inferences are structured into the green target costing process steps. However, the GTC approach is still in the testing phase in the construction sector. Besides that, the potential of the GTC and the incorporation of the value engineering tools show as great opportunity to reducing costs, ensuring profit margins and promote collaboration in the supply chain in order to evaluate the process of delivering value.

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References


USING MODULARITY TO REDUCE COMPLEXITY OF INDUSTRIALIZED CONSTRUCTION PROJECTS: A CASE STUDY

Daniela Viana¹, Iris Tommelein² & Carlos Formoso³

¹ Building Innovation Research Unit, School of Engineering, Universidade Federal do Rio Grande do Sul, Brazil, dietz.viana@ufrgs.br
² Project Production Systems Laboratory, Department of Civil and Environmental Engineering, University of California, Berkeley, USA, tommelein@berkeley.edu
³ Building Innovation Research Unit, School of Engineering, Universidade Federal do Rio Grande do Sul, Brazil, formoso@ufrgs.br

Abstract: It is widely known that industrialized building systems can positively impact construction projects in terms of efficiency, duration, safety, and quality. However, the introduction of prefabricated systems often results in the adoption of a technology that increases the speed of a single process, but at the same time creates an uneven flow between different processes on site and thus increasing the problems stemming from uncertainty and variability. This kind of sub-optimization tends to generate waste in construction sites, and thus constrains the potential benefits of using industrialized technologies. This paper explores some Lean Production ideas for improving the performance of industrialized building systems, based on a broader understanding of industrialization, including technical and organizational aspects as well as supply chain and information-related issues. The aim of this research study is to understand how the concept of modularity may help in reducing the complexity of industrialized building projects. This paper is based on a case study carried out in a steel fabricator company that had developed a modular structural chassis that makes it easy to integrate the steel structure with other building sub-systems. This chassis allows the company to offer an affordable and sustainable structural solution for a wide range of building types, including hospitals, medical office buildings, and high density housing. The main sources of data were analysis of documents, semi-structured interviews, and direct observations in construction sites. The results point out the role of modular systems in providing a product less prone to errors, which facilitates the adoption of open industrialized systems for construction projects. This case study also shows at which point in the development of building systems, Engineer-to-Order companies should spend more effort and time to reduce variability and uncertainty.

Keywords: Lean Production, Mass Customization, Modularity, Integration, Prefabricated Steel Structures.
1 Introduction

The idea of industrialized construction is often reduced to the use of prefabrication. Nevertheless, the term has evolved towards a broader approach in the last few decades, including technical and organizational aspects as well as the supply chain and information-related issues (Lessing 2006). The use of prefabricated components helps the construction industry to improve efficiency, speed, quality and safety, as it can potentially simplify the production process by both reducing the number of passes and parts to be installed in construction sites (Koskela, 1992), and clearly articulating by means of a limited number of alternatives how those parts will interconnect.

Perreira (1993) argued that construction has never made a large shift from manual work to hard automation, making it difficult to adopt flexible manufacturing methods in order to deliver customized projects according to customer needs, although this industry has indeed become more industrialized since the 1990s. Tommelein (2006) described industrialized construction as dealing with a complex supply chain because of the number of people involved in supplying a project, as well as uncertainty regarding the timing for requiring materials. The same author reveals how the sheer number and variety of types of materials being assembled in conditions subject to uncertainty is likely to affect the project duration. This is a problem, especially for companies that deliver Engineer-to-Order (ETO) products. Since the design of the product is not defined at the beginning of the project, designers tend to develop unique solutions for components, thinking it is a means to deliver value to the customer (Tommelein 2006). Although the uniqueness of the building as a whole may create value for the customer, uniqueness of individual components does not necessarily create such value; but in any case, the lack of standardization of components results in a production system that cannot really benefit from industrialization (Tommelein 2006).

Aggravating this situation, the design, fabrication and erection processes in the construction industry are commonly performed independently, either by a group of different companies or by various divisions of a single company (Perreira 1993), using buffers to decouple their work (Tommelein and Weissenberger 1999). This practice leads to problems, as the design of a structurally sound system may be difficult and costly to fabricate or erect. Difficult-to-fabricate connections, on-site struggling to plumb the structure, labour intensive processes, and rework are common examples of the consequences of the lack of integration (Perreira 1993).

In this context, modularity is an effective way of dealing with this challenge. It is based on the idea of decomposing a problem into functionally independent sub-problems, and then minimizing the interdependence between sub-problems (Kamran and Salhieh 2000). The interaction between sub-problems, or modules of the product, needs to be well defined and fundamental to the primary functions of the product (Ulrich and Eppinger 2004). In the construction industry, modularization simplifies the design, reduces the number of different components to be fabricated, and facilitates the final assembly of the building. Therefore, while the problem of on-site production could be reduced using industrialization, the problem of using one-of-a-kind products could be alleviated using pre-engineered products (Segerstedt and Olofsson 2010).

In order to make the construction industry more efficient and enable it to benefit from the use of industrialization, there is a need to rethink its traditional solutions. The adoption of modular systems means the development of innovative building solutions for the construction industry. As stated by Koskela and Vrijhoef (2001), the lack of understanding
of the construction problem may hinder the development of new technologies. The aim of
this paper is to understand how modularity can become a means to reduce the complexity
in the production flow between design, fabrication, and erection, focusing on steel
structural building systems. As part of this effort, this investigation explores how the use
of Lean Production principles can support this initiative, such as the reduction in the
number of passes and parts, lead time reduction, standardization, and supply chain
integration. This research study was based on a case study carried out in a company that
developed a beam-to-column connection for steel structural building systems.

2 Modularization as a means for dealing with uncertainty
The concept of modularity is useful in different fields for dealing with complex systems
(Baldwin and Clark 2000). In project management, Williams (1999) highlights that
complexity has two different dimensions: (1) the structural complexity, which is concerned
with the number of parts and their interdependences within the project; and (2) the
uncertainty, which is related to goals and methods for producing the project that are
unknown at the beginning. Crichton (1966) argues that the interdependence between parts
is also a source of uncertainty, since it makes it difficult to understand the impact of a
single change in the whole project. The change of a single part may interact with a myriad
of other parts of the project, generating changes in areas where the solutions had already
been defined.

Modularization is related to the decomposition of a product (or process), using standard
ways of interaction. A product can be analysed according to its functional or physical
elements (Ulrich and Eppinger 2004). The functional elements refer to the individual
operations and transformations that contribute to the overall performance of the product,
while the physical elements are the parts that implement those functions (Ulrich and
Eppinger 2004). This means that the functional elements are enabled through different
physical elements.

Physical elements are actually organized in blocks—so-called product modules—that
implement product functions. The organization of the functional elements into physical
modules and the way these modules interact is defined by the architecture of the product.
With this in mind, it is possible to analyse a product according to its modularity. The fewer
functions are implemented in each module, as well as the better defined the interaction is
between them (Baldwin and Clark 2000), the more modular the architecture is (Ulrich and
Eppinger 2004). The opposite of a modular architecture is an integral architecture of the
product.

Modularity means that there is interdependence within and independence across modules
(Baldwin and Clark 2000). For Baldwin and Clark (2000) this is one of the important ideas
that make modularity able to deal with complex systems. The second idea relates to three
concepts: abstraction, information hiding, and interface. Based on the assumption that it
is possible to deal with some problems by breaking them in smaller problems, those
authors suggest that modularization enables the isolation of a very complex part from the
others. This complex part can be thought through at a different level abstraction, hiding
some of its information by using a simple interface to the remaining parts. Therefore, it is
argued that modularity can be applied for both products and processes.

Lehtonen et al. (2003) point out that modularity cannot be seen as an isolated strategy for
the product development process. In fact, the whole production system needs to be
designed to depict the benefits from modularization. According to Ethiraj and Levinthal
(2004), the benefits of the modular design are well defined in the literature, but it is not clear how to divide a product into its modules.

Moreover, the benefits of modularity can be increased if other concepts related to industrialized construction are adopted, such as standardization and platforms (Lessing 2006). Standardization is concerned with the extensive and repetitive use of a solution that deals with recurring problems (Ulrich and Eppinger 2004). Thus, the use of modularization benefits from the use of standardization of products and processes. A platform (or chassis), in turn, is the use of a common set of components, modules, or parts in order to provide derivative products (Meyer and Lehnerd 1997).

Accordingly, buildings can be configured with components and parts from a platform into unique products, so that benefits are gained when the components of the platform are used to produce a variety of products with a common technological content (Lessing 2006). Bonev, Wörösch, and Hvam (2015) also emphasize the importance of the use of platforms as a competitive advantage in the building industry, as several projects can share common platforms.

The use of modularized components is an important step towards mass-customized solutions (Pine 1993). Mass customization refers to the strategy of a company to customize their products or services of a production system to provide a high variety of products at a reasonable price. Modularization is a means for achieving efficiency and reducing the costs. The interaction between modules forming a variety of products can provide the customization required by a mass-customized strategy. Duray (2002) emphasize that this customization should be related to the identification of customer requirements, not only a variety of options.

3 Research Method

This investigation is based on a case study of a company that developed a beam-to-column moment-resistant connection, designed to serve as a platform for producing steel structural building systems. This connection was conceived by Robert Simmons who founded ConXtech Inc. In fact, the innovation started with the development of the connection and ultimately evolved into a whole customized strategy for steel structures. This company has been recognized for raising benchmarks for productivity, speed, quality, and even safety in the construction industry.

The main sources of evidence used in the study were document analysis, including published articles, a set of three semi-structured interviews with production managers from the company, and three visits to the manufacturing plant. The goal of the interviews was to understand how production was managed and to understand the main problems faced by the company in delivering their projects. During the visits, the research team made direct observations of the production process and collected some data about the amount of material stored. By using multiple sources of evidence it was possible to increase the validity of the data available.

4 ConXtech Connection

In the 2000s, Robert J. Simmons realized the need to change how activities in construction sites were carried out, so he started his journey to find an efficient and safe method for producing concrete structures for high-rise buildings. However, he found out that the high cost of formwork and the lack of architectural flexibility of that type of structure made steel potentially a better option for developing an advanced industrialized solution for building structures (Renz 2005).
In the following sections of this paper, the mass-customized approach for producing the steel structure developed by ConXtech is described. First is a description of the modular design that enabled the company to create a platform for producing the structural components, with a limited set of options, yet still allowing an unlimited number of design configurations. Second is a discussion of the important events that affected the product development process.

4.1 Modular design

The development of a simple chassis for structural systems was based on the idea that the value of the structural system was not in its shape, but in its functionality. This became the starting point for the development of a modular system with a limited set of options. Using a mass-customized strategy, ConXtech was able to create a large number of design configurations by using modular design. This decision was based on the needs of the existing market. The creation of each of the connections described below was focused on fulfilling the design requirements of some specific market segments, ranging from mid-rise buildings to industrial buildings.

The sections of the beams and columns are always of the same type: flange beams and squared columns, also called hollow-structural section (HSS) columns, that are connected through a set of three different types of connections: ConXR (Figure 19), ConXL (Figure 20), and the gravity connection (Figure 21). The differences between the ConXL and ConXR connections are the size of the intersection, and the clearances allowed.

While ConXR has a single component welded to the column, which constrains the depth of the beam to the connection height, ConXL is developed to fit different heights. The latter connector is divided in two pieces welded to the beam, and another pair to the column, working as a trail to fit different dimensions. There are also gravity connections, used when no moment resistance is needed. These can be used around the perimeter of a building where there is less tributary load.
Using the connections as described, the company is able to offer four different systems: ConXR 100, ConXR 200, ConXL 300, and ConXL 400. The number stands for the dimension of the square column in millimeters. Each system is supplemented with the use of gravity beams, where required. All the systems are able to support a building up to 12 stories. The ConXR systems are ideal for 4 to 8 stories, while the L system for 2 to 10. According to the company records, the productivity of erection is higher in L systems since it covers larger spans, as shown in Figure 22.

<table>
<thead>
<tr>
<th>ConXR</th>
<th>Ideal for</th>
<th>Column size</th>
<th>Beam depth</th>
<th>Beam spans</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONXR 100</td>
<td>Small scale pipe rack structures and platforms for automated pallet retrieval systems</td>
<td>100mm</td>
<td>6” (variable weight)</td>
<td>4’ to 16’</td>
</tr>
<tr>
<td>CONXR 200</td>
<td>High-density residential and pipe rack projects.</td>
<td>200mm</td>
<td>12” (variable weight)</td>
<td>8’ to 20’</td>
</tr>
<tr>
<td>CONXL 300</td>
<td>High-density residential and pipe rack projects</td>
<td>300mm</td>
<td>14” to 24”</td>
<td>12’ to 30’</td>
</tr>
<tr>
<td>CONXL 400</td>
<td>Healthcare, military, data centre, commercial office, institutional, R&amp;D, parking and processing structures for industrial and energy &amp; natural resource applications.</td>
<td>400mm</td>
<td>18” to 30” for SMF and deeper for OMF</td>
<td>18’ to 45’+</td>
</tr>
</tbody>
</table>

The use of common shapes and sizes of structural elements was part of the company strategy to get easy supply of raw materials. The angle between columns and beam starts from 90 degrees and can be increased in 7 degree increments horizontally or vertically. Figure 23 illustrates the wide range of different structures that can be built using this technology.

Source: ConXtech, used with permission from Kelly Luttrell

Figure 22: Characteristics of the connection systems
The steel structure of a building is often thought of as an integral design. The product developed by this company can be regarded as an attempt of using modularity for this type of building system. The interface between modules is the connection between columns and beams, and each of those elements can be considered as a module of this system.

To facilitate the selection and specification of the company products by designers and structural engineers, ConXtech developed a BIM components library of their products that can be used by different BIM applications, such as Revit, ArchiCAD, and Tekla. BIM makes it easier to develop designs in conformance with the structural system constraints. Its use enables the designers to test product specification from the early stages of the design process, avoiding clashes and rework. Considering the fragmentation of the construction supply chain, particularly between design and production stages, the development of partnerships with designers that are able to use this solution is very important.

A major consequence of the use of modular design, facilitated by the use of BIM, is the reduction of design lead times, and the reduction in rework that otherwise is necessary for turning schematic design into shop drawings to be used in the manufacturing process. This approach also enables the company to provide timely cost estimates for the project. In an ETO environment, in which the customer demands cost and time estimates at the tender stage of the project (Stevenson, Hendry, and Kingsman 2005; Bertrand and Muntslag 1993), producing accurate estimates in early design offers a significant competitive advantage.

4.2 Cost effectiveness

A cost and productivity comparison was made between the technology from ConXtech and the conventional method, and presented in a research report produced by the Construction Industry Institute (CII) (Goodrum et al. 2013), considering the processes shown in Figure 24. Data from nine different projects from ConXtech were used as evidence. The results indicated that the conventional method required a higher number of production steps: there is a need to make a first alignment, then installing temporarily bracing, to finally make the permanent connection. By contrast, in the ConXtech solution,
when the top beam is placed, the connection locks the structure into place, making possible to make the subsequent bolting quicker.

Figure 24: Differences in the production process between the conventional method and the ConXtech solution (Goodrum et al. 2013)

It is worth noting that for such an accurate process the fabrication has to deal with accurate processes and machinery, making the cost for fabrication in plant higher than the conventional costs. Figure 25 shows the results of the comparative analysis regarding cost and productivity from Goodrum et al. (2013). The unit used to measure productivity was man-hours per tons produced. These data indicate that the productivity of ConXtech’s projects is much higher than the conventional solution, while the costs are almost the same.

Figure 25: Productivity and cost comparison between ConXtech and RSMEANS (Adapted from Goodrum et al. 2013)
This analysis made by the CII report is an important starting point for understanding this production system. It indicates that the company used fewer man-hour resources in construction sites than the traditional methods, yet it did not decrease the overall cost. This is because the fabrication process of this system is more expensive than the traditional process and, therefore, the control over resources and over the lead time for the on-site production process are crucial for the project to get the full benefits from this system. Therefore, it is important to understand the mean times needed for the production and erection process. Figure 26 depicts a typical schedule of a 3-story building of 5,000 m² (five thousand square meters). It shows how phases overlap and it highlights the short time spent in construction relative to the overall project duration.

![Figure 26: Typical project schedule](source: Authors)

### 4.3 Product Development Process

ConXtech was founded in 2004, after the development of the ConXR. Figure 27 shows important events in the product development process of ConXtech. In between the time from the development of the first connection until the founding of the company, there was a need to test the performance of the structural system under development. The idea of Simmons was to participate in the testing process, so that he could learn from the experience, instead of only analyzing an output report. With that in mind, they located a test-facility at the University of Arizona, headed by Prof. Robert Fleischman. In fact, Prof. Fleischman used to be the chief researcher in the ATLSS center that developed an innovative beam-to-column solution in the 1990s, but failed to commercialize it (Fleischman et al. 1995). When he first saw the ConX connection, he recognized the solution he had been looking for, years before.

Since the beginning of the product development process, the company created a virtual prototype for BIM platforms mentioned above. The virtual prototype was trademarked in October 2005, and is compatible with different Building Information Modelling (BIM) platforms.

The use of ConXR in the residential market showed was successful until the beginning of the US crisis in 2006. The slow-down in their main market was a trigger for the development of a different connection that could fit in different sizes of beams. In 2007, the ConXL was developed. A stronger connection, adaptable to different dimensions enabled the company to operate in other markets, such as commercial office, industrial/energy, healthcare, data centers, and temporary structures.
The company was recognized by the Construction Innovation Forum (CIF) in 2007 with the NOVA Award for the innovative system that had been developed. CIF is an international, non-profit organization formed in 1987, with the aim to encourage innovation for improving the quality, efficiency and cost effectiveness in the construction industry.

![Figure 27: Timeline of the ConXtech product development](image)

In 2008, the company was already working with both connections but in order to increase market awareness about the product, they developed an additional an in-house testing facility to be able to analyze the bi-axial performance of their structural systems in full scale. The results enabled the company to obtain acceptance by the Office of Statewide Health Planning and Development (OSHPD) for use in California hospitals, in 2010, followed by a certification by the Division of the State Architect (DSA) for use in California schools. Another important certification was the approval of the American Institute of Steel Construction (AISC) code committee and of the International Building Code.

The certification processes increased the use of the solution in construction projects. Given the resulting increase in demand, ConXtech decided to broaden its capacity by creating a certification program for other steel fabricators. Herrick Corporation was the first to be certified to produce the same structural frames, using ConXtech connections. The certification required the standardization of the main production processes so that they could be replicated in a different plant.

Since 2011, the company has been investigating the needs of industrial markets. It started from a modular structure, with standard clearances and no accessories, but then realized that if the remaining parts of the pipe rack were not modular, the effort required for the modular structure would not be as worthwhile as it could be. In 2014, the company released the modular pipe rack and its accessories, including stairs, floor panels, wall
panels, balcony and roof. All the accessories have a compatible module with the main structure, making all pipe-racks easy to produce.

4.4 Production Process

The structural elements (beams and columns) can be considered as commodities, and are bought-to-order from a service center, instead of directly from a mill, in order to decrease the delivery lead-time. The company has partner suppliers in order to have reliable delivery lead times, but when a higher demand is required, the use of common shapes and sizes facilitates the procurement of these from other suppliers.

The connections are produced by a foundry, and are bought-to-stock, as these are standard components. The connections delivered by the foundry are roughly finished. Therefore, the first activity in the plant line is the finishing of those components, called cut and drill. This process needs a high level of precision, and for that reason is the longer process in the line, taking up to 1h18min for a ConXR and 3h for ConXL to be produced. The process of welding connections to the structural elements adopts a five-minute takt-time. This process is carried out uninterruptedly, forming a stock of ready connections to be used in the production of the structural elements. From then on, the production sequence is defined according to the site installation sequence and rate that is agreed with the customer organization.

abriated products is batched according to the size of the truck that delivers them in the right sequence for erection. This is an important characteristic of this production system. The components are loaded on the truck in a last-in-first-out basis, so there may be adjustments in the batch so as to produce it in the correct order.

The collar connections are produced under a exceptionally tight tolerance control process allowing only a few thousandths of an inch of variation. By contrast, beams and columns sometimes lack dimensional accuracy, e.g., a squared section supplied to the company may be not precisely squared. This imposed a huge challenge in the manufacturing process of ConXtech. Instead of accepting this as an inherent characteristic, the company developed a set of jigs and fixtures in the manufacturing process to overcome tolerance problems. The welding of connections to beams and columns is a critical process, in which there is no room for deviations. A jig is used to enable horizontal welding both in the beams and in the columns, as shown in Figure 28.
The welding process of the collar connections in the beams is done by robots in order to achieve tolerances in the thousandths, regardless the tolerance of the structural component, as shown in Figure 29. The automated welding process is effective in terms of avoiding alignment mistakes. Column attachments are welded by people in the shop, using other jigs.

On the construction site, a challenge of using such a precise connection system was the allowable tolerances in the foundations where the columns should be placed. The solution adopted by the company was to decouple the uncertain and inaccurate process of construction of the foundation: the company developed an adjustable jig to precisely...
position the anchor bolt locations as needed for the superstructure, irrespectively of the accuracy of the location of the foundation, as shown in Figure 30.

Source: ConXtech, used with permission from Kelly Luttrell

Figure 30: Jigs to position foundations correctly

After the anchor bolts are put in place, columns are delivered and erected first, one by one. Then, the interior of the hollow tubular columns is filled with concrete to enhance strength, stability, and fire resistance. When the columns are ready, the beams are dovetailed in the columns. At this stage, the structure is already stable, and the workers can do the bolting stage. It is worth noting that the building is erected full height, in small areas so that ConXtech can quickly release the structure to the remaining trades, as shown in Figure 31.

Source: ConXtech, used with permission from Kelly Luttrell

Figure 31: Example of the erection process

During the erection process, there is no need for field welding. Two workers are able to place the beam and complete the bolting, as shown in Figure 32. The bolting process has a visual aid to avoid variability in the bolt tensioning, called Direct Tension Indicating (DTI) Squirter® washers (developed by another company). It consists of a nut with a flexible silicone embedded in the depressions under the bumps. The worker should tighten the
bolt until the calibrated amount of orange silicone appears from under the DTI’s squirt locations, then stop tightening. Therefore, only visual inspection is required, reducing the need for quality control and rework in this process.

The logistics in construction also benefits from the use of BIM. Logistics plans are produced as 4D models for defining the project phases, the position of cranes, the main flows of components, and lay down areas, as shown in Figure 33.

5 Conclusion
The study of ConXtech production system reveals a different way of looking to the problems considered normal in construction, creating new assumptions regarding how prefabricated products should be produced and even rethinking the role of the fabricator in construction project supply chains. This was possible by overcoming the tolerance problem from upstream processes and creating mistake-proof procedures at the manufacturing plant as well as site assembly.

The analysis of the product development process provided evidence that the company needed to be aware of requirements from its supply chain to be able to develop this
innovation. The sizes of the raw materials are based on nominal sizes, making the company to choose the best supplier in each point in time.

This solution can be compared to the product development of the Lexus car by Toyota. When Toyota decided to develop a luxury car, the only way to develop a light weight and quiet car was to cut noise, vibration, and harshness at the source (Liker 2003). The noise was largely driven by the accuracy with which the components were manufactured (Liker 2003). In both cases there was a need to reengineer the product to fit the customer requirements.

The decision for not including design in the company scope is an important part of the company strategy: use of the innovative connection is determined by licensed structural engineers. Among all the production phases, design is the most uncertain one, as the customer decisions have not been taken and their requirements were not yet fully understood. By working after this phase, ConXtech ensures that the level of definition is sufficient for its production system.

The production system was designed for responding to orders promptly. When an order is placed at the manufacturing plant, the goal is to fabricate and erect the structure in the shortest possible lead times. This is also a strategy to avoid uncertainty stemming from customer decisions, since production can start at the last responsible moment.

From this point of view, ConXtech can be considered as a make-to-order company, although the final product is configured according the customer’s design. The use of standardized and a limited number of components makes the company able to work with a low level of inventories, as well as to start production as soon as the order comes. According to Wiendahl, Von Cieminski, and Wiendahl (2005), the focus on decreasing the throughput time means working with a low level of work-in-progress (WIP). Those authors also highlight that this strategy means not making full use of capacity. As the type of product delivered by the company is dependent on a customer order, this strategy seems to be suitable. Moreover, the idea of working with a low level of WIP and with a continuous flow of production matches the lean philosophy. It is worth noting that the managers of the company were not aware of the lean philosophy when designing the system in the first place, though they are now. This case reveals how the use of continuous flow and low WIP levels triggers a better and easier-to-control environment, as claimed by Hopp and Spearman (2004).

References


A COMPARATIVE STUDY BETWEEN DRYWALL AND MASONRY PARTITIONS IN CONCRETE FRAMEWORK BUILDINGS

Jonas Silvestre Medeiros¹ & Murilo Blanco Mello²

¹,² Inovatec Consultores Associados Ltda., Brazil
¹ jonas@inovatecconsultores.com.br, ² murilo@inovatecconsultores.com.br

Abstract: From 2004 to 2013, the use of drywall as infilling partitions in concrete framework buildings had increased almost 16% per in average in Brazil. Although it sounds a reasonable rate, this would lead Brazil reach Chile’s 1.2 m²/hab consumption, for instance, only in 2024. Masonry is still largely used for partitions walls all over the country; even when associated with high wastes of materials and low productivity. Based on a field research where eight different projects were monitored for about one year, this study went into the measurement of wastes and productivity in order to discuss the reasons why local market still use traditional construction methods and what are the main barriers to the introduction of industrialized building methods. Results showed that the strongest barrier to the introduction of drywall is strongly linked education. Firstly, there are difficulties on coming to fair economic comparisons since reliable data and methodology are not available. Collected data showed that mortar wastes in masonry reached beyond 50% while masonry walls productivity average rate was 1.15 Mh/m² (man-hour per square meter). Gypsum boards in drywall wastes varied from 5 to 16% while its productivity average rate of drywall was 0.53 Mh/m². Applied in one of the monitored project, the replacement of masonry to drywall partitions represented a cost reduction of 2.2% of the project total cost, which made around 1.14 million USD savings. Secondly, dry wall installation is not well designed or planning and its impact is not clearly noticeable as it could be. There is a lack of tools, equipment and training programs to improve workmanship quality in general. Higher improvements would also be achieved if exterior wall and façade envelope were replaced by industrialized solutions like pre-fabricated panels, since the exterior envelope allows reducing the whole project schedule, while internal infilling not.

Keywords: Infilling Wall, Dry Wall, Masonry construction, Housing, Sustainable Construction.
1 Introduction
This study aims to compare building partition walls construction methods most common in Brazil: gypsum boards walls (known as drywall and here abbreviate as DW) and masonry block walls. In all projects analyzed along the field research both methods were specified, designed and built according to Brazilian technical standards and common practices of local market.

The paper consists of a cost comparison of an actual project chosen as a reference, based in site-collected data. Study development is represented in Figure 1.

Figure 1: Work phases included redesign of foundations, concrete framework and inner partition walls. On-site data collection of material waste and workmanship productivity and cost comparative analysis of masonry and drywall were the main parts of this study.

Although masonry – both ceramic and concrete blockwall – is considered the traditional way of walling in the market, drywall market share is growing continuously. In order to illustrate the Brazilian market on DW segment in recent years, the following data were compared in Figure 2: drywall growth rates, growth of building construction market in the country and growth of Portland cement consumption. (Carraro 1998).

DW corrected rate curve - which represents the difference between growth rate of DW and growth of building construction market - shows similar behavior of Portland cement consumption growth. Although DW growth rates could be slightly increased when taking into consideration gypsum imports, it is quite clear how DW growth rates dropped since 2013 due to construction activities slowdown.
This paper was developed in this market context. It aims to study masonry and DW infilling partitions construction methods in order to identify factors that may encourage the use of the more industrialized building systems in Brazil. Productivity levels and waste of materials data should be used in the near future as parameters to promote actions that can put forward a faster, rational and sustainable growth for the building industry in the country.

2 Productivity and waste

2.1 Methodology

2.1.1 Productivity

Souza (1996) defines productivity as the efficiency in the transformation of entries in exits in the process of building construction. The methodology to measure productivity is bases on the determination of the Unit Production Rate (UPR) where:

\[
UPR = \frac{\text{entries}}{\text{exits}} = \text{human labor (Hh) / amount of service}
\]

\[
UPR = \frac{\text{man-hour}}{\text{amount of service performed by the worker (m²)}} = \frac{\text{Mh/m²}}{}
\]

\[
UPR = \frac{(\text{worker (H) } \times \text{ work hours available (h)})}{\text{(m² of DW or masonry service)}}
\]

In all these expressions, the better the performance of workers are, the lower the UPR is.

The UPR can be calculated in different ways, however, in this study, three different forms will be used: the daily UPR, the cumulative UPR and potential UPR. The first index shows the daily productivity of a worker or a team. The second is the productivity during a certain period of time. The potential UPR is calculated from the daily UPR median, which values are lower than the cumulative UPR at the end of a period of study.

During the field data collection, two kinds of data were collected: the amount of worked hours directed involved with the service and the amount of service in square meters performed during the measurement period. In order to find more detailed results, DW installation and masonry steps were determined. Therefore, the total UPR would be the
sum of the results of intermediate steps such as positioning and fixing of the tracks, fixing of gypsum boards and joint taping should be summed up.

2.1.2 Wastes

Vargas (1997) defines waste as any resource that is spent in the running of a product or providing service beyond what is strictly necessary. It means that the wastes can both be applied to the workmanship and to any other building parts.

Two kind of wastes were determined: “embedded” and “residual”. The first consists of a material waste that remains at the site, as, for instance, the mortar that falls inside the blocks during the rise of a wall. The second is the kind of waste that leaves the job site to be disposed at a proper other place.

Waste is defined here, as the difference between actual and theoretical consumption of a material that has been used to a certain destination, expressed in percentage. The actual consumption is effectively observed during the measurements. The theoretical waste is the one original planned in the building budget. (Paliari 1999)

2.2 On-site measurements

2.2.1 Drywall

Four different projects that uses DW as infilling partitions were visited in different parts of the country according to Table 1. Their general description included main installation steps as shown in Table 2. Wastes measurement considered metal tracks, studs and gypsum boards.

<table>
<thead>
<tr>
<th>CODE</th>
<th>NUMBER OF VISITS</th>
<th>CITY / STATE</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>16</td>
<td>BARUERI / SP</td>
<td>COMMERCIAL/HOTEL</td>
</tr>
<tr>
<td>D2</td>
<td>40</td>
<td>JOÃO PESSOA / PB</td>
<td>RESIDENTIAL</td>
</tr>
<tr>
<td>D3</td>
<td>6</td>
<td>JUNDIAÍ / SP</td>
<td>HOTEL</td>
</tr>
<tr>
<td>D4</td>
<td>3</td>
<td>MOGI DAS CRUZES / SP</td>
<td>COMMERCIAL</td>
</tr>
</tbody>
</table>

Table 1: DW followed projects

<table>
<thead>
<tr>
<th>CODE</th>
<th>STEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Positioning and fastening of metal tracks</td>
</tr>
<tr>
<td>C</td>
<td>Installation of studs</td>
</tr>
<tr>
<td>E</td>
<td>Gypsum boards installation</td>
</tr>
<tr>
<td>F</td>
<td>Joints treatment</td>
</tr>
</tbody>
</table>

Table 2: DW steps

Results of on-site measurements productivity from the four DW projects are summarized in Figure 3 and 4.
As shown, project D3 had the best productivity results (lower cumulative UPR). Among the factors, that explains these results stands out the high repetition of a hotel wall layout. Work team was also better training and equipped. When compared, cumulative and potential UPR show that the project D3 obtained good averages results, with little variation between the daily and cumulative UPR. While project D4 showed cumulative UPR higher than D3, it got lower potential UPR. This result can be explained by the fact that project D4 has a higher variation among the daily measurements, resulting in lower UPR in some measurements and consequently lower potential UPR.

Table 3 shows different factors that have effect on productivity of each site visited. For each factor, a level of impact was associated. Positive and negative vertical arrows indicates their degree of importance. On-site measurement results of material waste for DW are presented in Figure 3.

<table>
<thead>
<tr>
<th>B – TRACKS POSITIONING AND FASTING</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of laser positioning system for installation for roof tracks</td>
<td>↑↑↑</td>
</tr>
<tr>
<td>Concrete framework geometric inaccuracy</td>
<td>↓↓↓</td>
</tr>
<tr>
<td>Use of removable scaffold</td>
<td>↑↑</td>
</tr>
<tr>
<td>Defect of fastening systems</td>
<td>↓↓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C – STUDS INSTALLATION</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studs smaller than the ceiling height</td>
<td>↓↓↓</td>
</tr>
<tr>
<td>Use of puncher for positioning</td>
<td>↑↑</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E – GYPSUM BOARDS INSTALLATION</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of walls</td>
<td>↑↑</td>
</tr>
<tr>
<td>Panels length according to ceiling height</td>
<td>↑↑</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F – JOINT TREATMENT</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of proper tools</td>
<td>↑↑</td>
</tr>
<tr>
<td>One step at a time on each every pavement (task division)</td>
<td>↑↑</td>
</tr>
<tr>
<td>Lack of planning for installation steps</td>
<td>↓</td>
</tr>
</tbody>
</table>

Use of more than one standard board instead of a high performance board | ↑↑↑ |
Large walls with little interference | ↑↑↑ |
No board positioning lay out | ↓↓↓ |
Need of double layer board | ↓↓↓ |
Team work in pairs (task division) | ↑↑ |
Prior installation of studs in the guides | ↑↑ |

Table 3: Productivity key factors for DW
As expected, the main wastes for DW is related to gypsum boards. Stands out in project D2 wasted of almost 20%.

In general, project D3 was the one that showed less wasted material. It is probably due to the higher repetition of walls layouts and better planning for cutting the boards and reuse of it. Table 4 shows factors that interfere in the productivity of each visited site. For each factor a level of impact is shown as described before.

Table 4: Waste key factors for DW

<table>
<thead>
<tr>
<th>C – STUDS INSTALLATION</th>
<th>LEVEL OF IMPACT</th>
<th>F – JOINT TREATMENT</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Studs smaller or much higher than ceiling requiring amends or cuts</td>
<td>↓↓↓</td>
<td>Number of building systems inside the walls</td>
<td>↓↓</td>
</tr>
<tr>
<td>Number of door framings</td>
<td>↓↓</td>
<td>Repeatability of walls geometry</td>
<td>↑</td>
</tr>
<tr>
<td>Loosen studs between guides</td>
<td>↓</td>
<td>F – JOINT TREATMENT</td>
<td>LEVEL OF IMPACT</td>
</tr>
<tr>
<td>E – DRYWALL BOARDS INSTALLATION</td>
<td>LEVEL OF IMPACT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boards length according to ceiling height</td>
<td>↑↑↑</td>
<td>Use of proper tools</td>
<td>↑↑</td>
</tr>
<tr>
<td>Planning reuse of boards</td>
<td>↑↑↑</td>
<td>One step at a time on each every pavement (task division)</td>
<td>↑</td>
</tr>
<tr>
<td>No layout of board</td>
<td>↓↓↓</td>
<td>GENERAL</td>
<td>LEVEL OF IMPACT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Workmanship training</td>
<td>↑↑↑</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stock and transportation of materials</td>
<td>↑↑</td>
</tr>
</tbody>
</table>

2.2.2 Masonry
As well as DW, four projects with masonry infilling walls were followed. Their general description and installation steps are shown in Table 5 and Table 6. Waste measurements considered blocks, mortar and plaster for rendering. Productivity results are summarized in Figure 6 and Figure 7.
Table 5: Masonry followed projects

<table>
<thead>
<tr>
<th>CODE</th>
<th>NUMBER OF VISITS</th>
<th>CITY / STATE</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>17</td>
<td>SÃO PAULO / SP</td>
<td>RESIDENTIAL</td>
</tr>
<tr>
<td>A2</td>
<td>25</td>
<td>JOÃO PEPEOA / PB</td>
<td>RESIDENTIAL</td>
</tr>
<tr>
<td>A3</td>
<td>55</td>
<td>JOÃO PEPEOA / PB</td>
<td>RESIDENTIAL</td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>SÃO PAULO / SP</td>
<td>RESIDENTIAL</td>
</tr>
</tbody>
</table>

Table 6: Masonry steps

<table>
<thead>
<tr>
<th>CODE</th>
<th>STEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Positioning of first row</td>
</tr>
<tr>
<td>C</td>
<td>Substrate preparation</td>
</tr>
<tr>
<td>D</td>
<td>Elevation</td>
</tr>
<tr>
<td>E</td>
<td>Fixation</td>
</tr>
<tr>
<td>F</td>
<td>Plastering</td>
</tr>
</tbody>
</table>

Project A1 shows the lowest cumulative UPR for masonry, including plastering. All steps in this project show better performance than other projects. On-site observation showed that the main factors for that was workmanship quality and wall detailing design.

There is a wide range among results from projects located in São Paulo (A1 and A4) and in João Pessoa (A2 and A3) shown a great difference in labor qualification.

Table 7 shows different factors that have effect on the productivity of each site monitored. Positive and negative vertical arrows indicates their degree of importance as described before.

On-site measurements results of material waste for masonry are presented in Figure 8. Mortar waste reached almost 70% in project A3. This high value is a result of imprecision of joints and lack of ability to deal with this material. Table 8 shows masonry constructions key factor for waste of materials.
Table 7: Productivity key factors of Masonry

<table>
<thead>
<tr>
<th>B – POSITIONING AND FIRST ROW</th>
<th>LEVEL OF IMPACT</th>
<th>C – SUBSTRATE PREPARATION</th>
<th>LEVEL OF IMPACT</th>
<th>D – ELEVATION</th>
<th>LEVEL OF IMPACT</th>
<th>E – FIXATION</th>
<th>LEVEL OF IMPACT</th>
<th>F – PLASTERING</th>
<th>LEVEL OF IMPACT</th>
<th>GENERAL</th>
<th>LEVEL OF IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of an independent team</td>
<td>↑ ↑ ↑</td>
<td>Use of simple or double spatterdash</td>
<td>↓ ↓</td>
<td>Task division and well defined workers responsibilities</td>
<td>↑ ↑ ↑</td>
<td>Need of previous leveling with cement render</td>
<td>↑ ↑ ↑</td>
<td>Quality of joint filling</td>
<td>↑ ↑</td>
<td>Making of one step at a time in the whole pavement (task division)</td>
<td>↑ ↑ ↑</td>
</tr>
<tr>
<td>Plan with accumulated dimensions for location</td>
<td>↑ ↑ ↑</td>
<td>Use of painted spatterdash</td>
<td>↑ ↑</td>
<td>Individual design for each wall including front view drawing</td>
<td>↑ ↑ ↑</td>
<td>Wall plane references previously setting</td>
<td>↑ ↑</td>
<td>Wall planicity</td>
<td>↑ ↑</td>
<td>Training and motivation of workmanship</td>
<td>↑ ↑ ↑</td>
</tr>
<tr>
<td>Slab well cleaning</td>
<td>↑ ↑</td>
<td>Framework quality</td>
<td>↑ ↑</td>
<td>Use of precast lintels and sills</td>
<td>↑ ↑ ↑</td>
<td>Need of thick layers of plaster for rendering</td>
<td>↓ ↓ ↓</td>
<td>Quality of blocks</td>
<td>↑ ↑ ↑</td>
<td>Idle due to lack of work front</td>
<td>↓ ↓ ↓</td>
</tr>
<tr>
<td>Physical axes for location</td>
<td>↑ ↑</td>
<td>Quality of blocks</td>
<td>↑ ↑ ↑</td>
<td>Inefficient delivery supply of material for the mason</td>
<td>↓ ↓ ↓</td>
<td>Mortar preparation on floor</td>
<td>↑</td>
<td>Mortar preparation on floor</td>
<td>↑</td>
<td>Compensation per square meter</td>
<td>↑ ↑</td>
</tr>
<tr>
<td>Slab leveling</td>
<td>↑ ↑</td>
<td>Mortar preparation on floor</td>
<td>↑</td>
<td>Number of openings with precast lintels and block layout adjustments</td>
<td>↓ ↓ ↓</td>
<td>Prior installation of plumb and square references tools</td>
<td>↑</td>
<td>Prior installation of plumb and square references tools</td>
<td>↑</td>
<td>Training and motivation of workmanship</td>
<td>↑ ↑</td>
</tr>
<tr>
<td>Plans of location of electrical and water systems</td>
<td>↑</td>
<td>Vertical lay out of wall avoids hollow blocks at the last row</td>
<td>↑ ↑ ↑</td>
<td>Use of precast lintels and sills</td>
<td>↑ ↑ ↑</td>
<td>Use of tube for mortar setting</td>
<td>↑ ↑ ↑</td>
<td>Use of tube for mortar setting</td>
<td>↑ ↑ ↑</td>
<td>Compensation per square meter</td>
<td>↑ ↑</td>
</tr>
<tr>
<td>Poor quality of pillar's side vertical alignment</td>
<td>↓</td>
<td>Levelling accuracy of slabs and beams</td>
<td>↑ ↑</td>
<td>Inefficient delivery supply of material for the mason</td>
<td>↓ ↓ ↓</td>
<td>Learning effects (quicker on upper floors)</td>
<td>↑</td>
<td>Learning effects (quicker on upper floors)</td>
<td>↑</td>
<td>Compensation per square meter</td>
<td>↑ ↑</td>
</tr>
<tr>
<td>Variation on apartments wall layouts</td>
<td>↓</td>
<td>Levelling accuracy of slabs and beams</td>
<td>↑ ↑</td>
<td>Number of openings with precast lintels and block layout adjustments</td>
<td>↓ ↓ ↓</td>
<td>Weight of block (concrete block)</td>
<td>↓</td>
<td>Weight of block (concrete block)</td>
<td>↓</td>
<td>Compensation per square meter</td>
<td>↑ ↑</td>
</tr>
<tr>
<td>C – SUBSTRATE PREPARATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E – FIXATION</td>
<td></td>
<td></td>
<td></td>
<td>GENERAL</td>
<td></td>
</tr>
<tr>
<td>D – ELEVATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F – PLASTERING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E – FIXATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F – PLASTERING</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>F – PLASTERING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GENERAL</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>GENERAL</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 8: Masonry projects material waste

Table 8: Waste key factors for masonry

<table>
<thead>
<tr>
<th>Category</th>
<th>Level of Impact</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B – POSITIONING AND FIRST ROW</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Too much mortar for first row</td>
<td>↓↓↓</td>
<td></td>
</tr>
<tr>
<td>Gathering the mortar excess</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td>Level of slab</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td>Blocks positioning planning</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td><strong>C – SUBSTRATE PREPARATION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of simple or double spatterdash</td>
<td>↓↓</td>
<td></td>
</tr>
<tr>
<td>Use of painted spatterdash</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td>Concrete framework quality</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td><strong>D – ELEVATION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual design for each wall including front view drawing</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Task division and well defined workers responsibilities</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Transportation of blocks with block carts</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Block cutting done for each worker</td>
<td>↓↓↓</td>
<td></td>
</tr>
<tr>
<td>Planning of mortar mixing for the following day</td>
<td>↓↓↓</td>
<td></td>
</tr>
<tr>
<td>Use of palletized block</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td><strong>E - FIXATION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mortar mixing at the job site (not) ready mixed product</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td>Excess mortar for laying blocks</td>
<td>↓↓</td>
<td></td>
</tr>
<tr>
<td>Poor quality of blocks</td>
<td>↓↓</td>
<td></td>
</tr>
<tr>
<td>Previous cutting of blocks when necessary</td>
<td>↑</td>
<td></td>
</tr>
<tr>
<td>Vertical joint filing during elevation</td>
<td>↓</td>
<td></td>
</tr>
<tr>
<td><strong>F - PLASTERING</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical layout of wall to avoid hollow blocks at the last row (top)</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Need of previous leveling with cement render</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Wall plane references previously set</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Need of thick layers of plaster for rendering</td>
<td>↓↓↓</td>
<td></td>
</tr>
<tr>
<td>Wall planicity referencies</td>
<td>↑↑</td>
<td></td>
</tr>
<tr>
<td><strong>GENERAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training and motivation of workmanship</td>
<td>↑↑↑</td>
<td></td>
</tr>
<tr>
<td>Stock and transportation control of materials</td>
<td>↑↑</td>
<td></td>
</tr>
</tbody>
</table>
3 Comparative Analysis

3.1 Methodology
This comparative analysis was based on one of the projects selected before for the on-site study. For the comparative analysis, partitions walls were considered first to be masonry and secondly DW.

3.2 Comparison between designs
A new DW design was prepared based on an original masonry performance. As DW design allowed to obtain the same performance (acoustic, thermal, and fire resistance) similar to masonry walls but with smaller thicknesses, it was possible to calculate a gain of approximately 320 m² area per building. In this project, this area represents an amount equivalent to two small apartments.

3.3 Evaluation of construction methods

3.3.1 Labor hiring and material acquisition
There are some differences between DW and masonry wall related to materials acquisition and hiring of labor. The main difference is that DW is usually sold both materials and labor by combined price. Therefore, technical and commercial responsibility is more centralized when compared with masonry. There is a single subcontractor or supplier from whom the general contractor requires and purchases it. Offers usually take into account the entire configuration. In other words, price varies according to materials specification and labor consumption per square meter.

In masonry construction, all activities are more dispersed. General constructor usually requires and purchase blocks, mortar, grout, and steel separately from different suppliers. This means that the masonry subcontractor do not take the whole work under its responsibility since materials and design are not included in the contract. Therefore, the general contractor have to deal with a larger number of suppliers, materials and logistics issues.

3.3.2 Productivity
Figure 9 and 10 put together UPR results for all DW and masonry projects. DW cumulative UPR is considerably lower than masonry. The average cumulative UPRs of projects is 0.5296 Hh / m², while masonry reached 1.1496 Hh / m². These values show that DW can be built twice as fast as masonry with the same number of workers.

Productivity values vary considerably among projects for both DW and masonry, showing that training and organization level varies significantly from one contractor or project to another. It is clear that even when a more industrialized method is used, productivity results can be disappointed. In other words, introducing new construction method is not only a question of marketing and selling force but also involves educational and training matters.
3.3.3 Wastes

Figure 11 shows DW material wastes measurements includes wastes of steel tracks and studs and gypsum boards. On the other side masonry wastes includes blocks, mortar and plaster for rendering.

Masonry showed higher wastes material rates when compared to DW. Mortar and plaster are particular too high and demands lots of vertical and horizontal transportation from the work site to the disposal site. Gypsum board wastes is close to 10 % which is considered to be high for an industrialized material. (Pinto 1989)
3.3.4 Wastes
An important point about wastes is related to the disposal of plaster and gypsum boards waste materials. In 2002, CONAMA - National Environmental Council for the Environment - published a resolution for the construction industry that says that all gypsum waste generated at the site must be collected and stored in a specific disposal location to avoid environment contamination. Gypsum boards must be separated, transported and disposal according to each city hall agency responsible for the environment an public cleansing. (CONAMA 2002)

Builders should prepare the work site areas to preventing plaster wastes from being contaminated with other materials and impurities. This process made it easier to separate materials for disposal afterwards. (SINDUSCON 2011)

Only Transshipment and Screening Areas (ATTS) licensed by each city are allowed to receive gypsum or plaster wastes, among other materials, which after triage and mixing procedures can be sold for recycling. Gypsum recycling methods have been studied since the late 90s and has made advances on reusing it for the cement industry, agriculture and even for the plaster processing industry. (Jacob & Besen 2006).

Since masonry needs to be rendered and it is the most common type of material for build partition walls, plaster is a main issue to deal with. This kind of render for walls result into a lot of waste and should be carefully considered.

3.3.5 Organizations and logistics at the job site
Constructions methods chosen for internal partitions walls have major impacts on organization and logistics at the job site. In order to understand it better two flowcharts shown in Figure 12 and 13. They show how materials are transported and move and where services takes place. It is remarkable how the use of blockwall involves significantly more activities, more site areas and transportation facilities when comparing to DW. Figure 14 to Figure 33 show a sequence of masonry and DW constructions steps.
Figure 12: DW materials flow and activities at the job site.

Figure 13 - Masonry materials flow and activities at the job site.
a. Material reception in two of the projects studied

Figure 14: Ceramic blocks are received at the construction site. General contractor manages acquisition and supply.

Figure 15: DW studs profiles being delivered at the site. Supply and transportation is under installer control.

b. Main stock of blocks and gypsum boards

Figure 16: Block stocks usually occupies a significant area inside the building to guarantee provision.

Figure 13: Gypsum boards are also stocked inside the building but demands a smaller area

Figure 18: Dry set bags of mortar for masonry are heavy and regular stocks.

Figure 19: Tracks and studs profiles stock placed outside the building without protection.
c. Mortar mixing and precast lintels areas

Figure 20: In this project a Portland cement, lime and sand mix where prepared at the job site.

Figure 21: Pre-casting of lintel for masonry at the job site

d. Intermediate stocks

Figure 22: Concrete blocks at the floor where masonry is just to be built.

Figure 23: Gypsum board at the floor where DW is just to be installed.

Figure 24: Dry set bags of mortar for masonry.

Figure 25: Steel studs for DW.
e. Construction

Figure 26: Technical staff check masonry design while first row of ceramic blocks is laid and leveled.

Figure 27: Team of two workers locate a drywall on a new floor.

Figure 28: Masonry wall with high concentration of embedded electrical systems. It is not very simple to avoid waste of material and time.

Figure 29: Drywall with electrical pipes in one of the projects of this study.
f. Waste

Figure 30: Ceramic block and mortar waste.

Figure 31: Gypsum boards waste.

Figure 32: Waste of plaster for masonry walls. About 2/3 of material are waste in some of the projects.

Figure 33: Waste of DW metal profiles show significantly lower volume when compared to other materials used in masonry.

3.4 Financial analysis

This part of the study aimed to review the original budget of project A1 changing part of infilling partitions from masonry to DW (Table 9). Originally, ceramic block masonry was used in project A1. The budget provided by the construction company was updated to allow a reasonable comparison. Drywall prices, including materials and services, took into consideration the average of three offers from known installers.

New foundation and concrete framework design were reviewed considering the new dead loads of DW which weight is about 20% of masonry. Since DW does not need any plastering, the cost of this rendering was not considered as well. Vertical transportation was also reduced since the second rack and pinion elevator mostly used for blocks and mortars was not necessary during the period that the infilling walls were built.

Two other general items were reviewed in the budget with DW: water consumption and waste transportation to a proper disposal site. As DW consumes much less water at the site than masonry, a saving in water consumption is expected. This saving was based on Passarelo (2008) study who estimate the proportional amount of water spent in the construction about 60% of all water used in the construction. Taking into consideration
that masonry takes three months of project A1 schedule, the saving of water would be about 7.2%.

Figure 9 show final cost comparison between budgets with masonry and DW for reference project A1. All value were originally determined in Brazilian Reais (R$) but were converted to USD exchange rate BRL 3.30 to USD 1.00 at August 29, 2016.

Table 8: Comparison between Masonry and DW budgets for reference project A1.

<table>
<thead>
<tr>
<th>COMPARISON</th>
<th>MASONRY</th>
<th>DRYWALL</th>
<th>RESULT</th>
<th>RESULT %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>909,091</td>
<td>905,782</td>
<td>-3,309</td>
<td>-0,36%</td>
</tr>
<tr>
<td>Foundations</td>
<td>131,1987</td>
<td>1,264,873</td>
<td>-47,114</td>
<td>-3,59%</td>
</tr>
<tr>
<td>Structure</td>
<td>10,835,754</td>
<td>10,644,938</td>
<td>-190,816</td>
<td>-1,76%</td>
</tr>
<tr>
<td>Infilling Walls</td>
<td>1,025,073</td>
<td>1,631,062</td>
<td>605,990</td>
<td>59,12%</td>
</tr>
<tr>
<td>Internal Rendering</td>
<td>1,736,953</td>
<td>529,648</td>
<td>-1,207,304</td>
<td>-69,51%</td>
</tr>
<tr>
<td>Painting</td>
<td>2,006,053</td>
<td>1,869,761</td>
<td>-136,292</td>
<td>-6,79%</td>
</tr>
<tr>
<td>Equipment</td>
<td>3,534,545</td>
<td>3,474,545</td>
<td>-60,000</td>
<td>-1,70%</td>
</tr>
<tr>
<td>Water</td>
<td>136,364</td>
<td>126,485</td>
<td>-9,878</td>
<td>-7,24%</td>
</tr>
<tr>
<td>Plaster Waste</td>
<td>30,303</td>
<td>20,805</td>
<td>-9,498</td>
<td>-31,34%</td>
</tr>
<tr>
<td>Other Wastes</td>
<td>217,424</td>
<td>139,152</td>
<td>-78,273</td>
<td>-36,00%</td>
</tr>
<tr>
<td>Other Services</td>
<td>30,327,987</td>
<td>30,327,987</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Global Project Cost</td>
<td>52,071,533</td>
<td>50,935,039</td>
<td>-1,136,494</td>
<td>-2.18%</td>
</tr>
</tbody>
</table>

When changing the infilling walls from masonry to DW there are two main kinds of reduction on waste transportation: block / mortar wastes and plaster wastes. In project A1 the reduction obtained to block and mortar wastes was 36 % in volume which represents about 774 dump buckets. To plaster, the reduction was 31 % in volume, which represents about 78 dump buckets. These reductions represent respectively 60,000 USD and 10,000 USD. Similar results for block, mortar and plaster wastes were also obtained by Malia (2010) and Dias (2013).

Table 9 shows that most highlighted difference in the compared budgets was the plaster render of masonry walls. Even costing about 60 % more than masonry per square meter, DW results in global costs saving was 2.18% or 1.14 million dollars.

3.5 Economic-Financial Analysis

The economic index applied to the comparison was Net Present Value (NPV). Typically, NPV is used for payments and receipts. However, as values of entries for the project cash flow were not available, NPV was used to analyze the impact of differences in monthly disbursements due to the substitution of internal partition walls to DW.
All original project data considered for masonry, including construction schedule and budget where provided by the construction company and designers. DW early deadline was postponed four months when compared to the original schedule for masonry. Its price including materials and services and took into consideration the average of three subcontractors offers.

This study consider the average National Index of Construction Cost (INCC in Portuguese) of 0.435% per month obtained from 2013 to 2015, to calculate the disbursement over the time of project. (FGV-IBRE 2015)

3.5.1 Construction schedule and planning
Figure 34 shows with balanced lines physical schedule of project A1 with original masonry infilling partition walls and then with DW replacing it.

As seen, DW construction has to follow the sequence of other activities production like concrete framework and external masonry walling, not taking advantage of better productivity. Even when DW get started four months after external masonry, it has to follow the completion of other services to get started. In other words, changing only internal infilling masonry wall to DW does not modify the final project deadline.

3.5.2 Results
Table 10 show NPV results for total project cost based on the different disbursement flow analyzed. This table show results obtained to masonry and DW and the final result between them.
Table 9: NPV final differences in costs for masonry and DW in Project A1.

<table>
<thead>
<tr>
<th>NPV</th>
<th>MASONRY X DW</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASONRY</td>
<td>- 45,370,445 USD</td>
</tr>
<tr>
<td>DW</td>
<td>- 44,368,657 USD</td>
</tr>
<tr>
<td>DIFFERENCE (USD)</td>
<td>1,001,798 USD</td>
</tr>
<tr>
<td>DIFFERENCE (%)</td>
<td>-2,21%</td>
</tr>
</tbody>
</table>

4 Conclusions

Results showed that the main barriers to the introduction of industrialized constructions method like drywall in Brazil is strongly linked with education. Manufacturers, contractors and specifiers have difficulties on come up with fair economic comparisons since reliable data and calculation methodology are not available.

Several aspects raised during observations at the construction sites inhibit the improvement of DW market in the country. In this sense, stands out poor detailing designing in order to integrate other building parts such as installations, waterproofing and final coverings. Poor planning and training of drywall installers were issues present at all monitored sites. Tools and equipment were clearly not enough to allow a good quality installation. In other words, introducing a construction method in a new country is not only a question of marketing and selling force but also involves technical educational and training matters.

Productivity and wastes on-site measurements demonstrated that the installation of DW is in average two times more faster than masonry and generates much less waste of material even considering that block walls have a reasonable level of rationalization in Brazil.

Collected data showed that laying mortar wastes in masonry reached beyond 50 % while masonry walls productivity average rate was 1.15 Mh/m² (man-hour per square meter). Gypsum boards in drywall wastes varied from 5 to 16 % while its productivity average rate was 0.53 Mh/m².

DW is offered including both material and service but it is not turning into advantages to the client since the general constructor usually pays the same price for it. To address this situation this trade logic should change to contribute to a better competitive scenario.

Although the cost of DW is much higher than the masonry - around 59 % in this study - the benefits of the system can result in savings of 2.18 % of the total cost of the project.

Higher improvements would also be achieved if exterior wall and façade envelope were replaced by industrialized solutions like pre-fabricated panels, since the exterior envelope allows reducing the whole project schedule, while internal infilling not.

The authors suggested here a list of actions to improve DW market in Brazil:
a) encourage technical publication about productivity and wastes as well as a detailed method to calculate reduction of direct and indirect costs of DW;

b) disseminate of successful cases focusing on design and installation best practices;

c) issue of a technical design and installation guide for architects and engineers;

d) create a new national institutional training program for professionals and students;

e) create a new national institutional training program for installers focused on best practices and planning.

References


PINTO, T.P. Perdas de materiais em processos construtivos tradicionais. São Carlos, 1989. Departamento de Engenharia Civil, Universidade Federal de São Carlos – UFSCar.


Abstract: Solar photovoltaic (PV) system has been providing important environmental and social benefits as compared to other traditional energy resources, which contribute to the development of sustainability. The photovoltaic market in the world has grown very high to a capacity of 27.4 gigawatts in 2011. These are good signs because generation of electricity from photovoltaics does not produce any greenhouse gases emissions, making it an option to replace fossil fuels and create employment opportunities and improvement in economic condition even in areas, which are still developing. However, manufacture of PV components has some effects on the workers and the surrounding environment throughout their life cycle that starts from extraction and acquisition of raw materials, to production, discarding, and recycling. Large production of PV components also require land area that is not available or may compete with other uses of the land. This poses big problems, which are considered solid obstacles to further utilize the PV technology. The production of solar modules includes numerous explosive, flammable, and toxic chemicals. In this study, the Building Integrated Photovoltaic (BIPV) technology has been reviewed while discussing advantages and disadvantages. Moreover, the paper is also highlighting the current state of this renewable source as well as looking at the future challenges this technology may face, particularly in the building sector. Lastly, what would be the role of this renewable energy source and how it will respond or compete with other renewable energy sources. This review has been completed by an extensive literature review and conclusions were drawn summarizing the findings that would benefit the building sector, and professions like architects and engineers.

Keywords: Renewable Energy Source, Advantages of Building-Integrated PV, Sustainable Development, Disadvantages of Building-Integrated PV, Challenges in BIPV.
1 Introduction

1.1 Advantages of Building Integrated Photovoltaics

Solar Photovoltaic Panels are certainly the first thing that people think when they discuss renewable energy sources such as solar energy. It is known that within one hour, the solar energy from the sun is sufficient to compensate the energy consumption of the human beings for a whole year. With this, going green through the solar Photovoltaic panels or PV panels is conceivably the right path to take. But the current solar energy technology that we have, may still fall behind in harvesting this massive quantity of energy, which is totally free in nature.

To further discuss, we have outlined the advantages and disadvantages of using Solar PV panels, specially BIPV (Building Integrated Photovoltaics) as a source of electricity, to power up the needs of the human life. It is a perfect solution to use photovoltaic systems in providing the basic needs of energy of the current and future societies. Photovoltaic systems can be a channel for a sustainable mix of energy, which is eco-friendly, by realizing their important advantages.

Photovoltaic systems are eco-friendly. In comparison, the conventional power is generated out of fossil fuels and photovoltaic systems use solar power, which is green and renewable energy to produce electricity. Hence, carbon dioxide emissions going to the atmosphere are greatly decreased that eventually lessens the ‘greenhouse effect’ significantly. Further, photovoltaic systems like other renewable energy resources do not emit harmful gases towards the atmosphere, which badly impacts the environment and the health of the people (Green 2011).

Architects and Engineers in Australia, United States, Japan, and Europe are currently exploring the ground-breaking ways of integrating solar power in the design of buildings. This is because of the following advantages of BIPV systems:

- PV support structure uses the building itself.
- Electrical System Interface is simple and easy with just a connection to an existing distribution panel.
- BIPV materials replace traditional building labor and materials, which reduce the net installation cost of the PV system.
- On the spot production of electric power avoids imported and carbon-based electric energy.
- Integration based on architectural approach makes it acceptable by industry market.
- BIPV systems signify the building owner’s expression of eco-friendliness (Prasad and Snow 2005)

Other benefits from BIPV systems can be summarized as follows: It provides natural daylight, superior design, solar shade, and top leaders in manufacturing as against less quality construction materials and design, it can be custom made with unrestricted design patterns which use crystalline or thin film PV modules to achieve thermal performance, light transmission, and higher power output, and BIPV glazing units increase architectural enthusiasm and allow users to produce electric power independently from electric utilities, also limitless designs of BIPV integration, which includes atriums, gas stations, entrances, shaded parking areas, sky lighting, and covered walkways, commits and supports LEED Green Building Certification from the US Green Building Council for photovoltaic and natural daylighting, and decrease in infrastructure costs, also skylight intrusions allow internal wiring connections. Turn-key projects allow BIPV sky lighting, which composed of solar skylight array designs, effective coordination of electrical devices, and skylight
components and accessories in addition to expert BIPV installers (Sweets.Construction.Com 2014).

1.2 Disadvantages of Building Integrated Photovoltaic

On top of the advantages of the BIPV systems, there are also disadvantages that should be carefully taken into full consideration. First, there is environmental impact of photovoltaic system. The waste during the production and extraction when leaked into the soil significantly affects the aquatic Eco toxicity. It is therefore advised not to use zinc in the assembly of support structure. Engelenburg and Alsema (1998) highlighted that phosphine and saline are both combustible gases as well as very toxic, which are both, used in the production of modules. Theoretically speaking, these gases should not be emitted, but some cases emissions can happen hence these gases must be considered one of the concerns (Monsonet 1998).

Second, there is a potential for human health effects because of the chemicals that are used in the manufacture of photovoltaic devices. The effects are categorized as follows: (1) carcinogenic effects and (2) non-carcinogenic effects. Non-carcinogenic effects mean that the chemical does not support growth of cancerous tumor for animals and humans. Non-carcinogenic effects have symptoms like reduction in appetite or growth, and it impacts on the immune system, nervous system, reproductive system and some specific organs. Carcinogenic chemicals promote development of cancerous tumor in animals, humans or both. These chemicals will have also other bad effects on the health of people. Non-carcinogenic effects due to chemicals are gauged based on the several toxicity factors initiated by the US Environmental Protection Agency (EPA) and some other state agencies. The parameters of measurement include the skin absorption rates, direct contact reference doses, inhalation reference doses, and oral reference doses. The toxic strength of the chemical depends on the manner of entering into the body either through inhalation or orally.

Few volatile and toxic gases, corrosive liquids, and alleged carcinogenic chemical compounds are used in the manufacture of photovoltaic devices. Fthenakis and Moskowitz (2000) highlighted that the extent of the potential effects on human health varies based on the period of exposure, rate of occurrence, intensity, and the chemical’s toxic properties. The probability for humans to be exposed to these chemicals happen during the assembly process, due to leaching of broken or cracked modules, or due to burning of the modules (Fthenakis & Moskowitz 2000). Moskowitz (1995) stressed out humans are more vulnerable to health risk related to photovoltaic devices during the manufacturing process of these devices and not during the installation works. Due to the higher probability of risks during the manufacturing of these devices, widespread efforts and works have been completed on methods to decrease the dangers to workers in manufacturing plants as highlighted by Moskowitz (1995). There is also a high risk for the neighboring residences near the manufacturing plants due to untoward events, which may release the toxic gases like large blast in the manufacturing plant. But this event is a very rare to happen, and no report has been made so far regarding the same (Pier 2004).

Third, photovoltaic manufacturing affects the environment since the process involves the usage of electricity. It is very important to consider the energy used in manufacturing these devices because of 100% renewable energy was used, the impact on the environment would be less. There are different ways to gauge the environmental effects, such as waste, acidification, global warming, the energy required, and the raw materials that were exhausted during and after the manufacturing. There are hazardous materials required for manufacturing, such as silane used to purify silicon as well as toxic chemicals like
phosphine and diborane used for doping the silicon. These gases are not dangerous during the manufacturing but once leakage happens due to an accident, it will be very dangerous to the environment. To emphasize, dangerous gases like solvents, phosphine, diborane, silanes, and silica dust are released during the manufacture of photovoltaic devices.

There are limited studies regarding the impacts on the economic and social aspects because most of the research focused on the technical aspects of the photovoltaic devices. It is however very difficult to know the impacts because the first generation solar panels will have an effect after 25 years only and the technology is new and the life cycle could take long time (Dubey et al 2013).

1.3 Overview of BIPV System and Its Current Use
Building integrated photovoltaic or commonly known as BIPV system is a combination of building construction and solar photovoltaic electric technology. This topic is very interesting for those people who are into building design and conservation of energy. BIPV focuses on the sustainability concept, which aids the people to enhance their life as well as to protect the mother earth. Photovoltaic can be an integral part of a building into many various assemblies such as the following:

- Solar panels can be installed on the building’s façade which replaces the traditional spandrel glass. Most of the time, they are installed vertically which decreases access to the available solar energy, however the wide surface area of the building counter the power loss.
- Photovoltaics can be installed into awnings and saw-tooth aspects on a building façade. This enables access to the sunlight and at the same time improves the architectural aspect like passive sharing.
- Applications of photovoltaic in roofs can directly replace the commonly used 3-tab asphalt shingles, as well as the seam and batten metal roof systems.
- Utilization of PV in skylight systems shows its economical and beneficial feature (Prasad & Snow 2005).

BIPV system consists of components that provide any one of the following functionality in addition to the generation of electric power; weather proofing; integrates easily to building aesthetics; protects from sunlight or provides shadows; provides thermal insulation; does not produce noise, and is safe (Sinapis & Donker 2013) as shown in (Fig.1).

BIPV has an impact on every facet of the design stages in comparison with other installation process in a building construction, such as the following: Orientation and layout of the building, massing and form of the building, planting system and layout and height of
the surrounding buildings, strategy on energy consumption, construction of the building and its modularity, selection of other building materials, systems, and components including its assembly, costs of capital and operations, integrity and details of the construction, architectural and building appearance, and custom made for the owner and occupants of the building.

BIPV presently contributes a small but significant portion of the PV market globally. The value of PV in the world market is around 1,200 megawatts last 2010 but is projected to increase by 56% on a compound annual growth rate and surge to around 11,400 megawatts capacity by 2015 (Kujawa 2011) as shown in below graph (Fig. 2).

Currently, BIPV system is used in various integration application types, such as roofing system, skylights or canopies, and solar facades or curtain walls.

1.4 BIPV Roofing Systems

BIPV roofing systems are different from conventional PV systems in many areas. First, the material used is a flexible and thin film, which is not rigid. The material can be accustomed to the shape of the mounting surface at an extent. Second, the flexible material can be installed to correspond to the shape of the mounting surface and not directed against the sun. Third, the flexible material has lower efficiency as compared to the rigid panels. However, flexible materials can be made through different manufacturing methods and technologies. The efficiency and cost of both products are dependent on the installation technique, manufacturing methods, and technology used.

The component of BIPV roofing systems is a typical roofing material, which has a fiberglass, reinforced polyester membrane and the flexible material is placed on top of it. Normally, the existing roof is installed with a solid insulation. The insulation is made to fit the conduit that will enclose the wiring required to link each BIPV segment into the electric system. Then, a conventional roof membrane covers the insulation. Lastly, a secondary roof membrane, which contains the PV materials, is put on top of the first membrane. The PV is now connected and the electric joint boxes are enclosed with roofing material that completes the installation. The electrical connections are then finalized that connects the PV to the load or electric grid. To clearly demonstrate this procedure, Techval selected the thin PV film from Uni-Solar. This product has an exceptional triple junction capability that improves the capture of a broad scale of light. This distinctive characteristic enhances the production of increased energy in kilowatt-hours during the whole daylight period. It is efficient in conditions like low light and cloudy skies and utilized TEFZEL, a protective sheet like a Teflon, which resist debris, hail, wind, and seismic conditions. Thin film technology does not use glass, which makes it very flexible, durable, and rugged. When the PV is integrated into the roof panels, it becomes an important component of the whole
roof assembly. BIPVs generate the same energy like other photovoltaic system types and provide an extra roof insulation that reduces the cooling and heating costs. This assessment did not cover the cooling and heating impacts to the interior of the building. The generation of energy from the roof decreases the building’s energy consumption from the utility’s power grid (NAVFAC EXWC and ESTCP 2013) as shown in (Fig.3).

Figure 3: BIPV roofing system (Martin 2011)

1.5 BIPV Sky Lighting System

Glass roofs or atria are normally built by a sealing and securing transparent glazing units to a steel or aluminum frame that is pre-installed. The method is the same as that used in constructing glass house. Atria commonly occupy large spaces and considered to be the roof structure of commercial towers and buildings. When the glass roof tends to be more inclined, the technology turned more into like a facade, specifically in the method of securing laminations. In contrast, skylights penetrate a typical roof assembly to give ventilation and light. Skylights in domestic buildings composed of a single framed glazing unit opening on the roof space. Other skylight systems commonly used in large open plan establishments like shopping malls and warehouses composed of lengthy stretches of glazing units and significantly help the lighting needs of the building. Opaque panels can be used on the parts facing towards the sun and transparent windows directly opposite the sun. Skylight and atria technologies are very strong and perfect fit for PV integration because semi-transparent PV laminates can be used as direct replacement for the glazing units.

Any wiring interconnection can be inserted through the structure. For single glazed skylight units, a Module Integrated Inverter (MIC) may be installed into the structure. Because the PV cell controls the quantity of transmitted light, semi-transparent modules are produced by keeping space between opaque cells in a non-transparent module, or by adjustment on the thickness of deposited layer of amorphous silicon. Assessment of the heating and lighting requirements helps in determining the required spacing or desired transmission capacity of the PV cells (Zaki 2013).

The following photo shows semi-transparent roofing systems and skylights (Fig.4). These assemblies are normally a combination of glass and glass laminates that adjust the transmission of light and inspire the architectural design of shadow and light (Sinapis & Donker 2013). Super Sky’s BIP skylights are categorized in various design configurations as follows; single slope skylights, ridge skylights, and pyramid skylights.
1.6 BIPV as Facades System – Curtain Walls

Another method of integrating photovoltaic in a building is through its walls, or at times to be more effective, through a curtain or so-called multi-purpose skin that surrounds the interior or core of the building. Compared to other types of BIPV, this type also serves double purpose. As stressed out by Ray Noble (2011) in his presentation during the Small Business Development Center (SBDC) Conference, it is not required to optimize the direction of the cells aside from northward or southward directions as long as the PV modules have competitive price against the typical building materials and have been designed intelligently into the building. He highlighted that this will also produce electric power of up to 90% of its rated power efficiency. Therefore, it is definitely not required that modules should be installed on the rooftop (Martin 2011).

There are a number of alternatives to determine how to install PV in other section of the building aside from the roof. These are coarsely discussed in the following, however the method of installation will depend on the strategy of the designer.

- Integration into the walls. Vertical walls receive some radiation from the sun particularly if the building is at higher locations in which the winter sun rise at low angles, but they do not get the same quantity of solar radiation like horizontal or slanted roofs do. Modules which are perforated have the ability to capture a part of radiation to produce electric power in the cells at the same time allows some light to pass through inside the building.

- Integration of modules on to the ‘skin’, which surrounds the building. Various buildings are built with a so-called ‘skin’ to control climate conditions and for aesthetic purposes. Panels, which can be opened and closed like windows have the ability to directly control the building’s climate and at the same time keep sufficient space to maintain coolness, making it, function proficiently.
Solar awnings as mentioned earlier have the advantage of avoiding unwanted solar radiation to hit the eyes but utilize them to produce electric power. The angle of solar awnings could be significantly changed to best block or capture the sun’s radiation based on the season.

- Semi-transparent and windows facades – Photovoltaic glass windows, which are semi-transparent have the ability to produce electric power at the same time reduce the infrared and ultraviolet radiations of the sun. The windows can be available with a full variety of tailor-made options to achieve the building code, climate, weather, and design requirements and are normally made from PV glass laminates. Acoustic and thermal insulation can be attained when layers of glass are added to the base unit of a semi-transparent module of PV glass (Pagliaro et al 2010).

2 Challenges with BIPV System

Present time show that BIPV constitute around 1% from the total installations of PV in the world, however numerous analysts predict that this technology will progress in the near future. The following numerates the barriers and challenges that may affect or hinder the good progress of BIPV unless the concerned stakeholders take care of these properly.

2.1 Cost

Fig. 7 below shows the high costs, which post as a major challenge for BIPV that also requires the presence of State aids such as tax incentives and subsidies to decrease the prices. The residential installation has an average capacity of 3 kW with an expected average cost of 8s/W, hence the overall cost for a tailor-made BIPV integration will be more than s 24000. This makes many states such as Italy and France to offer maximum feed-in-tariffs for BIPV systems to assist BIPV investors in acquiring loans from the bank. BIPV system’s high price as compared to the typical PV system makes BIPV systems to be installed most of the time on the roof. At this very moment, the only installations aside from on-roof installations are big esteem projects, which uses highly customized PV modules (Pagliaro et al 2010).

![Figure 6: PV sun shade (Pagliaro et al 2010)](image)

**Table IV.** BIPV Market: Average Cost per Watt of a BIPV System (Europe), 2007 (Source: Frost & Sullivan, 2007).

<table>
<thead>
<tr>
<th>Company</th>
<th>Module (€/W)</th>
<th>Inverter (€/W)</th>
<th>Component cost (€/W)</th>
<th>BOS costs (% of total)</th>
<th>Total system cost (€/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost range</td>
<td>1.5-23.0</td>
<td>0.4-3.0</td>
<td>2.1-35.0</td>
<td>6-40.0</td>
<td>3-41.0</td>
</tr>
<tr>
<td>Average cost</td>
<td>4.3</td>
<td>0.7</td>
<td>5.0</td>
<td>11.0</td>
<td>6.58</td>
</tr>
</tbody>
</table>

![Figure 7: BIPV market (Pagliaro et al 2010)](image)
2.2 Performance
Several critical variables with regard to performance have to be considered to calculate the energy costs of BIPV systems. Initially, BIPV modules compared to rack-mounted PV system have chances of experiencing increased operational temperatures because airflow between the host structure and module are not permitted due to the modules being flush by the building surface. Increased temperatures may damage the semiconducting material of the PV modules, which can reduce the conversion efficiency more rapidly and hasten early damage. Certain PV materials like amorphous silicon have higher integration potential and are more vulnerable to accelerated damage due to increased temperature as compared to others. PV materials having higher integration potential like flexible PV technology and thin films usually have lesser efficiency initially and for this reason may add to an increase in the cost of energy.

Lastly, since BIPV modules generally have less semiconducting materials unlike traditional PV modules, a BIPV system will most probably generate reduced electric power in comparison with a flat-panel system having the same dimensions. Even if BIPV system increases its PV-suitable space in a building, factors like less optimal angle of solar irradiation on vertical surfaces plus blockages due to neighboring buildings decreases the investment on module utilization (Lowder 2012).

2.3 Legal and Administrative Barriers (Barriers for the introduction of PVs in the Building Sector)
Administrative and legal barriers refer to the issues regarding the policies of various parties involved in the development of photovoltaic technology.
- Some listed buildings do not allow BIPV: Listed building refers to a building, which is officially selected as special in terms of cultural, historical, and architectural importance. Hence, a listed building is not possible to demolish extend, or change without the special approval from the municipal planning authority. This indicates that BIPV cannot be implemented in any part of an existing listed building.
- The electricity grid is difficult to access: Generally speaking, in almost all EU nations, the proper access to the low voltage grid has to be controlled and the methods for the grid-connection have to be simple. Particularly for BIPV, there is a lack of standards to improve this application. Further, there is also a shortage in the long-term PV installation and sustainable programs as well as long-term goals in several nations (EPIA 2008).

2.4 Perception Barrier and Technical Barriers
Perception barriers refer to the shortage in knowledge and the false information from the media that underrate the extra value of photovoltaic system, which block their incorporation into the building systems:
- The benefits of PV are not vivid to the clients and architects.
- BIPV is treated as not aesthetical and could not attract architects.
- Knowledge about BIPV has limitations for the architects, developers, and planners.
- Change of criteria for behaviour and purchasing is required from local authorities.
- Acceptance of the need to include the BIPV from the project conception to the process of construction by the end-users, developers, contractors, and architects.
- Lack of knowledge of the uprising role in the consumption of electricity.

Technical barriers are associated with the problems about structural that the installers, architects, and engineers experience during the design, engineering and installation of PV systems into the building system. The normal PV system is composed of a few interconnected modules, such as photovoltaic array and connected to a range of inverters.
that change the electric energy generated by the modules to the electrical features of the network. Some people thought that putting modules on the building roof is easy. However, some roofs are not designed for supporting the additional weight, and some are again not designed with proper orientation, or even the shade is present due to the buildings nearby or the building itself in which it is substantially needed to modify the installation of the PV systems. (EPIA 2008).

3 Conclusions
This paper provided us the advantages and disadvantages of BIPV. The advantages of BIPV panels are first; photovoltaic systems are eco-friendly, as it does not produce carbon dioxide emission when generating electricity. Secondly, photovoltaic systems are one of the dependable technologies for the utilization of the energy from the sun, which means the source of energy is limitless. Third, BIPV systems can operate independently and does not produce disturbances and noise pollution unlike the wind power technologies. Fourth, photovoltaic systems require only little maintenance in comparison with other renewable energy resources. Lastly, photovoltaic systems with latest technological advancements are steadily becoming more common because of its success in decreasing the cost as apparent in the present photovoltaic industry. Further disadvantages were also discussed like the potential effects of this resource to human race and our environment. The current state of the technology for this resource was also tackled which emphasized the development method in order to enhance the current technology and innovations. Then, the challenges faced by this resource were also shown on different aspects such as its costs and performance.

Hence, this review paper established that the solar photovoltaics technology is one of the reliable and dependable energy resources for the coming generations. The lack of knowledge about solar photovoltaics will result in non-utilization of the unlimited energy sources that is always available and free to use. It is a fact that BIPV system would still need a lot of improvements but current tests and experiments could provide strong knowledge and experience to further explore the maximum potential of this energy source, in order to give the whole world more benefits for the human race and to maintain sustainability in our environment.

References


CONCRETE MASS FOR ADDITIVE MANUFACTURING

Chingis Daulbayev\textsuperscript{1}, Mikhail Rodin\textsuperscript{1}, Yerkhan Aliyev\textsuperscript{1}, Behrokh Khoshnevis\textsuperscript{2}, Zulkhair Mansurov\textsuperscript{1}

\textsuperscript{1} Institute of Combustion Problems, Almaty, Kazakhstan, e-mail: chingis.daulbayev@yandex.ru
\textsuperscript{2} University of Southern California, Centre for Rapid Automated Fabrication Technologies, USA, e-mail: khoshnev@usc.edu

Abstract: Current work describes experiments on identifying setting time of concrete mass, which could be used as a construction material for 3D Printing technology. Many experts are interested in application of additive technologies for the construction of buildings. However, there are a huge number of problems, solving one of which is the decreasing of setting time of concrete. It is important that the concrete will be a multi-layer, which imposes certain requirements. The main problem is in the selection of the optimal composition for concrete having the desired properties. A complex of various additives have been used to obtain such properties like compressive hardness, fluidity under the influence of vibration. As a result of the work additive accelerates has been received for decreasing the setting time of concrete. The setting time was determined by a penetrometer in accordance with international standard. Due to such composition of additives, the setting time of concrete decrease up to 10 minutes, which is sufficient for the use of such composition for the construction of buildings using 3D technology. The experimental setup allowed demonstrating the process of setting and hardening of concrete without the use of formwork. This paper describes the method of determining the setting time, optimal chemical composition was picked up, allowing not only to increase the setting time of the concrete mass, but also does not affect the mechanical properties.

Keywords: Setting time of concrete mass, 3D printer, cement, chemical composition
1 Introduction

3D-printing technology is developing rapidly, conquering the world and this is a real technological revolution occurring right before our eyes. A method of creating layered object based on its volumetric 3D model is widely used in mechanical engineering, electronics and medicine. Production by volumetric printing method prosthetic hands, skull and other parts of the human body does not cause any doubt, the use of such technology for the construction put under a big question. One of the first who announced the possibility of applying this technology has been the leading developer of the project Contour Crafting – Roboting Construction System - Behrokh Khoshnevis (Kwon 2002:147-160). The idea proposed by a professor of the University of Southern California, is as follows: on pre-cleared land a great 3D Printer something reminiscent of dockside crane is installed. The construction of the house starts from the basement. For this purpose, facility operator gives the appropriate command to mechanism, and the workers have to ensure the continuous supply of a special wet and quickly solidifying concrete. 3D-printer for construction has a nozzle or extruder that extrudes fast-hardening mixture. The surface on which three-dimensional object is constructed, named as working area and it’s sizes set by step value of the nozzle. Moreover, formwork is not needed, in other words, construction setup of volumetric printing is declared as a self-contained mechanism. By connecting electricity, such mechanism could literally create a finished building out of nowhere (Zhang 2012:5-6).

There are several ways to create volumetric structure:

1. Layered extrusion of viscous working mixture. In this case, the extruder squeezes, like toothpaste from a tube, jelly-like mass of concrete with additives that accelerate the setting time.

2. The method of selective sintering.

By this technology in the working area of 3D machine the working mixture melting occurs, melting is achieved in relation to the construction, by focused laser or a sunbeam, and normal sand is used as working mixture. It is known, at the time of writing this paper that the only existing sample of such a device belongs to inventor Marcus Kaiser, student of the Royal College of Art.

3. The method of spraying / component glue.

Particularly, it is known that the working sample of the Catalan Institute of Advanced Architecture (IAAC) (Peter Novikov Group) named as Stone Spray Robot, and the system D-Shape, designed by Enrico Dini (Monolite UK, (a private company)) for the construction of buildings. During this process, jet of sand comes from the working nozzle, which is immediately mixed with the adhesive composition / catalyst, forming a volume at a given point.

From the listed methods of forming the volumetric objects, attention of builders is attracted, in the first place, to the method of layering extrusion because it is already established sufficiently large bearing surface and the real houses. However, in the course of a detailed study of this technology raises a number of questions, and to answer some of them a decent monograph is required. One of the problem is the creation of a concrete mix, which should have a number of properties that will ensure the required quality of construction of houses and architectural structures.

In order for the extruder can print, the concrete mixture should have the following properties:

1. The setting time should be about 15-20 minutes depending on the complexity of the architectural pattern that is required for the construction of one layer of concrete wall.
Layered growing involves layered construction, i.e. extruder, controlled by software, will spread the entire structure layer by layer. Depending on the complexity of the model, the time spent on the construction of a single layer of the house will vary.

2. The viscosity of concrete mix has to change due to vibration, namely the mixture must be in a liquid state when vibration is applied. After the extruder squeezes the mixture it needs to keep the form that sets by nozzle form. In fact, without vibration concrete mixture almost immediately should keep in shape. Generally, in the world, these technical problems are solved now; however, the chemical composition of the additive in the concrete is a trade secret.

3D-printers in construction - a production robotization, a kind of a conveyor. Naturally, all related industries in this chain must comply, firstly structure of printer itself, extruder, software, working mixture production, solving TSP problem, logistics (if the solution is prepared near to constructing object then the service is not needed), warehouse component format (creating a shared for the whole village or allied industry transports the party to a particular house). For these and other issues decision, undoubtedly, will be offered. Experts, conducting the development of volumetric printing technology, are very active. 3D techniques are being introduced into society. If during the presentation of Behrokh Khoshnevis, held in 2012, cautiously called the years 2017-2020 as the beginning threshold of the building robots operation, in reality, already in February 2014 a series of real houses was demonstratively printed in China (Reichel 1981:125-131).

Application of concrete additives of accelerate the setting time is possible only in accounting its influence on the reinforcing properties (Afanasiev 1989:72). Application of polymeric fiber size of 5-10 microns and diameter of 300 nm would enhance reinforcing property. However, the reinforcing by using with iron rods is need too (Bazhenov 2004:256).

1.1 Experimental

Additives for accelerating the setting time of concrete have been known for several decades. There are entire institutions involved in the solution of various problems [4]. The main problem occurred in finding the optimal composition for concrete having the desired properties, which were mentioned above. To obtain these properties, a complex of various additives was used. To develop the technology of preparation of fast-hardening mixture the mode of action of accelerator hardening depending on the feeding point in its process of preparation of the cement slurry was investigated. For the preparation of fast-hardening cement the cement, sand and chemicals were used as a feedstock. In Table 1, there are different chemical additives that are using to decrease the setting time of concrete

### Table 1: The data of the cell growth and substrate loss

<table>
<thead>
<tr>
<th>№</th>
<th>Reagent name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calcium nitrate (HA)</td>
</tr>
<tr>
<td>2</td>
<td>Calcium chloride (HK)</td>
</tr>
<tr>
<td>3</td>
<td>Sodium nitrite (NK)</td>
</tr>
<tr>
<td>4</td>
<td>Calcium nitrate-nitrite (NNK)</td>
</tr>
<tr>
<td>5</td>
<td>Nitrite-nitrate calcium chloride (NNHK)</td>
</tr>
<tr>
<td>6</td>
<td>Threenatriumphosphate (TNF)</td>
</tr>
</tbody>
</table>

Table 2 shows the properties of all the additives that have been used, it is should be noted that the optimal composition are consists from different chemical additives.

### Table 2: Characteristics of concrete mass with accelerators
Comparing the test results of concrete samples setting with accelerating additives the complex composition additives (PID-1) has been identified that eliminates the shortcomings of each. The use of calcium chloride for instance can cause corrosion of reinforcements that is unacceptable during the construction of houses. Experiments were carried out based on the largest concrete strength with the optimal content of additive.

Table 3: Concrete mass strength determination using different kinds of additives

<table>
<thead>
<tr>
<th>Additive type</th>
<th>% of additive, by weight of cement</th>
<th>Compression strength [kg/cm²] at the age (in days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>NNK</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>120</td>
</tr>
<tr>
<td>PID-1</td>
<td>3</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>150</td>
</tr>
<tr>
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<td>150</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>NNHK</td>
<td>3</td>
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<td></td>
<td>7</td>
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<tr>
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</tr>
<tr>
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<td>10</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3 shows that the use of a complex additive PID-1 not only speeds up the setting time of concrete, but also increases the compressive strength. The ratio of water and cement is 0.44.

Then a series of experiments on Vick instrument were conducted for which a certain size cement blocks were made (State Standard 24211-91), wherein the weight ratio of cement, sand and chemical reagent was 122 gr / 244 gr / 7.2 gr, 10.8 gr and 14.4 gr respectively. After testing all types of reagents, it has been found that the best result was shown by PID-1 with the percentage of 3-15% of the total cement mass.

Table 4: Fast-hardening cement mixture content

<table>
<thead>
<tr>
<th>Chemical reagent</th>
<th>Additive reagent in % by weight of the cement mixture</th>
<th>Initial set, min</th>
<th>End of setting, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID-1</td>
<td>3</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>14</td>
<td>35</td>
</tr>
</tbody>
</table>
It has been shown that the addition of PID-1 in amount of 3-15 % reduces setting time that is sufficient for the technological needs of a cement solution using 3D printer (Table 4). The figure below shows photographs of the samples obtained with the addition of PID-1 in the cement solution.

Figure 1: Samples with addition of PID-1 in the cement

Measurements of the setting time of cement slurry obtained due to the Wick device. It consists of a certain weight load and the needle that under the force of gravity penetrated into the cement block. One can determine the setting time by the depth of penetration.

After defining of concrete setting accelerator experimental setup for testing the mechanical properties of the solution was constructed. The experimental setup consisted of a nozzle, which is free moved in one direction. This installation allows to print wall thickness of 4 cm and length of 80 cm and a height of 60 cm, solution squeezing occurs by force of gravity of the mixture itself. Since the plastic pipe was used in this pioneering design, it is worth mentioning that there is no vibration, because such pipe greatly dampens vibrations. Figure 2 shows photographs of printed wall.

Figure 2: Front side of the printed wall
The thickness of each layer was 2 cm. Above photographs show the front side of the wall. It should be noted that there was not any treatment for each layer, which proves the correctness of the selected additives. Installation design allows a slight smoothing of a single layer. The time interval between layers was 10-15 minutes.

Moreover, due to this installation 35x35 cm square of height around 14 cm was made. For a complete test the solution effectiveness with additives worth be noted that in order to achieve all the desired properties of the concrete mix the complex of additives should be used. Mass of all additives in the aggregate do not exceed 4% of the weight of concrete solution.

In combination with the PID-1 it is planned to use plasticizers that are polar compounds of carbon radical having hydrophobic and hydrophilic groups with polarizing properties. Plasticizing agents in percentage content less than 1% of the total concrete mass.

References

BAZHENOV, Y. M., 2004, 'Concrete technology, building products and constructions', Concretes and mortars Textbook for high schools, pp. 256.


Abstract: The Internet of Things has brought about a wave of connected wireless technologies and devices for use within the building sector. The building automation sector has not been left behind with the introduction of technologies such as EnOcean. Connected wireless technologies have come down significantly in recent years and this paper provides anecdotal evidence from practitioners in the industry of the compelling financial and flexibility of using EnOcean sensors against conventional wired sensors.

Keywords: EnOcean, Building Automation, Wireless Battery Free Sensors, Sensor Technology, Energy Efficiency.
1 Introduction

EnOcean GmbH is the developer of the patented energy harvesting wireless technology marketed under the Dolphin brand. Headquartered in Oberhaching, near Munich, the company produces and markets self-powered wireless sensor solutions for batteryless applications in the Internet of Things, which are used for building and industrial automation, smart homes and LED light control. According to the official website, EnOcean products are based on miniaturized energy converters, ultra-low power electronics and robust radio technology in open standards.

With the proliferation of internet enabled devices, there has been a growing demand for more data and the need for equipment and machines to communicate with the users. Such demands manifest the need to have smarter, internet enabled things especially within the building sector where significant opportunities are available to process large volumes of sensor data to make our daily lives easier safer and more comfortable (https://www.enocean.com/en/company-profile/ accessed 22 November 2016).

Data today is a commodity prized among large corporations with many companies building analytics to make sense of large data sets to produce insights that was never thought possible. Energy data today can be used and manipulated to provide alarms and alerts to warn users of impending failure to certain electrical equipment as well as location of certain electrical failures.

2 Industry and market overview

The collection of data can only be done through the installation of sensors and power meters within a building. Installation of sensors and power meters can be easily done for new constructions as part of the construction work however becomes a challenging coordination task when plaster ceilings are erected and interior fit outs completed.

The introduction to building automation into existing buildings have proven to be challenging within existing buildings in Malaysia due to the high capital expenditure required as well as the operational challenges of wiring up the building with RS 485, fiber optics, Cat5e or Cat6 cables. These barriers have commonly dissuaded building owners from embarking on complex building automation projects, depriving them of deep energy savings that can be obtained through building data analytics and machine learning.

Retrofit of buildings with building automation systems often required extensive and intrusive work within tenanted spaces to install a wired network of cable backbones within the building risers to allow the transfer of data between the sensors, controllers and data managers. This work often entails night work and can take up to twenty four (24) months to complete. This challenges building owners with the need to balance the need to maintain the equipment within the building against the administrative and operational hassle of carrying out such complex undertakings for extended periods of time.

Recognizing the conventional cable sensor installation method limitations, low powered and open wireless technology has been touted as a suitable solution to avoid labour intensive cabling works within buildings. Many different wireless technologies exist. An apt comparison of the technologies was published by (Harneet et al 2013) as shown below.
According to (Gomez et al 2010), the primary goal of wireless technology is to reduce installation cost and labour work. Two major building automation communication protocols exists in the market which are sold under the brand name Zigbee and EnOcean. Although wireless was once considered unreliable for building applications, Table 2 above has shown that wireless technology has overcome many of its earlier problems with interference and signal reach. Both technologies have unique offerings and strengths however this research paper will only focus on EnOcean due to its battery free solutions which avoid the installation of an additional power cable to power up the sensors.

### 3 Use of EnOcean from the Malaysia building rating tool perspective

The use of EnOcean sensors would complement the attainment of credits awarded by local Malaysian rating tools such as Green Building Index, GreenRE and MyCrest. These tools award existing building owners with credits for the use of building automation systems as well as providing the tools to commission the building. EnOcean also provides building owners with the flexibility to implement improvements to building automation either as a standalone system of as a complementary system to its existing building automation system.

A summary of the direct credits available for building automation system and use of sensors from the different rating tools is summarized below:
<table>
<thead>
<tr>
<th>Green Building Index</th>
<th>GreenRE</th>
<th>MyCrest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Energy Efficiency Performance (EE1) - 1 – through the installation of an energy management control system</td>
<td>ENRB 1-8 Energy efficient practices – 2 - for use of energy efficient products</td>
<td>EP – 26 – 1 - for building energy audit where sensors will be used to collect the data continuously</td>
</tr>
<tr>
<td>Lighting zoning (EE2) - 3 – through the provision of individual lighting zones, provision of auto sensor controlled lighting in conjunction with daylight strategy and provision of motion sensors</td>
<td>ENRB 1-8 Energy efficient practices – 4 - for energy saved from use of energy efficient products</td>
<td>EP 29 – 3 – for recommissioning of building through the use of sensor data</td>
</tr>
<tr>
<td>Energy efficiency monitoring and improvement (EE8) - 1 – through the use of sensors to provide data to the energy management system to track system performance</td>
<td>ENRB 4-1 Indoor air quality performance – 3 in total with 1 credit for an effective IAQ management plan, 1 credit for room temperature display and 1 credit for carbon dioxide display</td>
<td>OH 12 – 1 – for monitoring of air temperature and relative humidity</td>
</tr>
<tr>
<td>Carbon dioxide monitoring and control (EQ3) - 1 – through the installation of CO₂ monitoring system</td>
<td>Innovation - 1 – though the use of wireless battery free technology which is maintenance free</td>
<td>Innovation - 1 – though the use of wireless battery free technology which is maintenance free</td>
</tr>
<tr>
<td>Mould prevention (EQ5) - 1 – though the installation of humidity sensors to ensure humidity indoors is less than 70% RH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal comfort: controllability of systems (EQ6) - 1 – through the installation of temperature sensors to provide feedback to the ACMV system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Innovation - 1 – though the use of wireless battery free technology which is maintenance free</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total = 9 credits</td>
<td>Total = 10 credits</td>
<td>Total = 6 credits</td>
</tr>
</tbody>
</table>

4 Methodology
A desktop research was carried out based on data of an existing building that was fitted out in July 2016. Data was obtained from the construction cost of a single floor office interior fit out project. Normalized rates for wiring was subsequently calculated to determine the cost of installation of commonly used building sensors such as daylight...
sensors, motion sensor, temperature and humidity sensors and lighting switch points. Upon completion of the interior fit out construction, a quotation was obtained from an EnOcean product systems integrator on the cost to install EnOcean enabled daylight sensors, motion sensor, temperature and humidity sensors and lighting switch points within the same office space. Both pricing estimates were derived to ensure that both have the necessary data collecting hardware and data processing software.

5 Analysis
A summary of the cost to install the conventional and EnOcean enable wired daylight sensors, motion sensor, temperature and humidity sensors and lighting switch points is shown in Table 3 and Table 4 below:

Table 3: Costing for EnOcean fit out at the office building

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Qty</th>
<th>Unit</th>
<th>Unit Price (RM)</th>
<th>Total Price (RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Officer Room 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>1 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>1</td>
<td>unit</td>
<td>357.50</td>
<td>357.50</td>
</tr>
<tr>
<td>2.2</td>
<td>2 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>1</td>
<td>unit</td>
<td>422.50</td>
<td>422.50</td>
</tr>
<tr>
<td>2.3</td>
<td>230Vac Flush mounth 1 channel remote control switch receiver relay EnOcean 868Mhz</td>
<td>3</td>
<td>unit</td>
<td>1,170.00</td>
<td>3,510.00</td>
</tr>
<tr>
<td>3.0</td>
<td>Meeting Room 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Ceiling Occupancy Sensor EnOcean 868Mhz Cell Power</td>
<td>1</td>
<td>unit</td>
<td>926.25</td>
<td>926.25</td>
</tr>
<tr>
<td>3.2</td>
<td>1 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>1</td>
<td>unit</td>
<td>357.50</td>
<td>357.50</td>
</tr>
<tr>
<td>3.3</td>
<td>2 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>1</td>
<td>unit</td>
<td>422.50</td>
<td>422.50</td>
</tr>
<tr>
<td>3.4</td>
<td>24Vdc power wall box mounted PUK 2 dimming channel 1-10V relay EnOcean 868Mhz</td>
<td>3</td>
<td>unit</td>
<td>1,153.75</td>
<td>3,461.25</td>
</tr>
<tr>
<td>3.5</td>
<td>Multi-Purpose Manager for general control and gateway functionalities completed with 64Mb flash Ram, 4GB storage BACNet Interface</td>
<td>1</td>
<td>unit</td>
<td>2,100.00</td>
<td>2,100.00</td>
</tr>
<tr>
<td>3.6</td>
<td>230Vac/24Vdc/50Hz 20VA DC Power supply, and 230Vac/24Vdc/40VA power supply included enclosure</td>
<td>1</td>
<td>unit</td>
<td>680.00</td>
<td>680.00</td>
</tr>
<tr>
<td>5.0</td>
<td>Data Manager Area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Indoor Light Level Sensor EnOcean 868Mhz Solar self power</td>
<td>1</td>
<td>unit</td>
<td>1,105.00</td>
<td>1,105.00</td>
</tr>
</tbody>
</table>

HOR_B88 500
### Table 4: Costing for conventional system fit out at the office building

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Cat6e cable (RM)</th>
<th>Power cable (RM)</th>
<th>Device (RM)</th>
<th>Unit Price (RM)</th>
<th>Total Price (RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Officer Room 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>1 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>280</td>
<td>110</td>
<td>60</td>
<td>450.00</td>
<td>450.00</td>
</tr>
<tr>
<td>2.2</td>
<td>2 gang switch colour white EnOcean 868Mhz Cell Power</td>
<td>280</td>
<td>110</td>
<td>80</td>
<td>470.00</td>
<td>470.00</td>
</tr>
<tr>
<td>2.3</td>
<td>230Vac Flush mount 1 channel remote control switch receiver relay EnOcean 868Mhz</td>
<td></td>
<td></td>
<td>255</td>
<td>255.00</td>
<td>765.00</td>
</tr>
</tbody>
</table>

**Conventional System**

Original Total for Part B: **14,000.00**

Total Price without GST: **47,768.75**

6% GST: **2,866.13**

Total Price with GST: **50,634.88**
<table>
<thead>
<tr>
<th>3.0</th>
<th>Meeting Room 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Ceiling Occupancy Sensor EnOcean 868Mhz Cell Power</td>
</tr>
<tr>
<td>3.2</td>
<td>1 gang switch colour white EnOcean 868Mhz Cell Power</td>
</tr>
<tr>
<td>3.3</td>
<td>2 gang switch colour white EnOcean 868Mhz Cell Power</td>
</tr>
<tr>
<td>3.4</td>
<td>24Vdc power wall box mounted PUK 2 dimming channel 1-10V relay EnOcean 868Mhz</td>
</tr>
<tr>
<td>3.5</td>
<td>Multi-Purpose Manager for general control and gateway functionalities completed with 64Mb flash Ram, 4GB storage BACNet Interface</td>
</tr>
<tr>
<td>3.6</td>
<td>230Vac/24Vdc/50Hz 20VA DC Power supply, and 230Vac/24Vdc/40VA power supply included enclosure</td>
</tr>
<tr>
<td>5.0</td>
<td>Data Manager Area</td>
</tr>
<tr>
<td>5.1</td>
<td>Indoor Light Level Sensor EnOcean 868Mhz Solar self power</td>
</tr>
<tr>
<td>5.2</td>
<td>2 gang switch colour white EnOcean 868Mhz Cell Power</td>
</tr>
<tr>
<td>5.3</td>
<td>24Vdc power wall box mounted PUK 2 dimming channel 1-10V relay EnOcean 868Mhz</td>
</tr>
<tr>
<td>5.4</td>
<td>230Vac Flush mount 1 channel remote control switch receiver relay EnOcean 868Mhz</td>
</tr>
<tr>
<td>5.5</td>
<td>Indoor Temperature and Humidity Sensor EnOcean 868Mhz Solar Self Power</td>
</tr>
<tr>
<td>5.6</td>
<td>Indoor CO2 sensor EnOcean 868Mhz 24VDC powered require</td>
</tr>
<tr>
<td>5.7</td>
<td>230Vac/24Vdc/50Hz 20VA DC Power supply included enclosure</td>
</tr>
<tr>
<td>6.0</td>
<td>Wiring Conduit, Trunking Works</td>
</tr>
<tr>
<td>6.1</td>
<td>Power supply for the control EnOcean device module</td>
</tr>
<tr>
<td>6.2</td>
<td>Wiring interlink cabling at DB board, flush mount control cabling c/w junction box and terminal block</td>
</tr>
<tr>
<td>7.0</td>
<td>Testing and commissioning &amp; cabling loop check, termination works</td>
</tr>
<tr>
<td>8.0</td>
<td>Training, O&amp;M, Drawings</td>
</tr>
</tbody>
</table>
The table above provide a bill of quantity and costs for the Schneider SmartStructure Lite against conventional sensors. It is to be noted that the cost for the conventional system above does not include the labour cost to install the data cables within the spine of a building and any hacking required to install additional power cables for the light switches and loss of revenue caused by disruptions to building operations. This cost was difficult to estimate and varies with the age of the building and business operations of the building. It can be seen from the tabulation in the tables above that the cost of the conventional system for a single floor retrofit is not significantly cheaper than the EnOcean solution.

6 Conclusion

It can be seen that while the initial purchase cost of wireless products is higher, the author has not included the life cycle cost in this study. The study has also not accounted for the shorter faster turnaround time for implementation. Building owners, and consultants should take the extra step to evaluate the advantage of wireless sensors to automate building controls that previously could not be cost-justified.

The data collected also indicate that building owners can easily conduct a low-risk, low-cost pilot test of wireless sensor installation to find out if it will be effective unlike traditional building control solutions, which require a sizeable installation investment just to find out if it will be effective.

Acknowledgements

The author would like to acknowledge Edgenta Energy Services Sdn Bhd for providing the necessary data used in this paper and Resource Data Management for the costing information on its data manager and software.

References


SESSION III - MGEEB PAPERS
A TECHNO-ECONOMICAL FEASIBILITY STUDY OF OIL PALM FROND (OPF) CEMENT BOARD

Nor Azlina binti Ramlee¹, Shaikh Abdul Karim Yamani² & Mohd Edyazuan Azni¹c

¹Malaysian Institute of Chemical and Bioengineering Technology, Universiti Kuala Lumpur, 78000 Alor Gajah, Malaysia, and University of Applied Science Rosenheim, 83024 Rosenheim, Germany, n_azlina_ramlee@yahoo.com and edyazuan@unikl.edu.my
²Faculty of Applied Sciences, Universiti Teknologi MARA, Malaysia, syamani@pahang.uitm.edu.my

Abstract: In recent years the development and application of lightweight, sturdy, durable and eco-friendly construction materials have been of great interest. Fibres from oil palm frond (OPF), produced in substantial amounts as a by-product of the palm oil industry, may be a promising alternative to asbestos cement board currently available in the market. OPF cement boards were produced at three different OPF to cement ratios (1:3.5, 1:4.0 and 1:4.5) with a thickness of 25 mm and a density of approximately 600 kg/m³. The mechanical and physical properties of OPF cement board such as modulus of rupture (MoR), modulus of elasticity (MoE), tensile strength, thermal conductivity, thickness swelling and water absorption after 24 hours of immersion in water were determined in accordance with Malaysian Standard MS 934:1986. Scanning electron microscopy (SEM) showed that the optimum amount of OPF particles mixed with cement can fill micropores and make a uniform structure with a rough surface which improves properties of cement board. OPF cement board with a ratio 1:3.5 demonstrated the best mechanical and physical properties with MoR of 18.8 MPa, MoE of 2569 MPa, thickness swelling of 0.48% and a thermal conductivity of 0.099 W/m.K. These properties fulfil the MS 934 requirements and are as good as the currently available fibre cement boards in the market.

Keywords: Oil palm frond OPF, particles, cement board, eco-friendly
1 Introduction

The oil palm (Elais guineesis Jaq) is a major agricultural lignocellulose crop in Malaysia. According to the Malaysian Palm Oil Board (MPOB), Malaysia is the world’s second largest palm oil producer. The oil palm is a uniquely resourceful and sustainable plant in being not only economically valuable and productive but potentially providing trunks, oil palm frond (OPF), and empty fruit bunches as raw materials for a range of wood based product (Yusuf, 2004). In the year 2008, Malaysia generated approximately 51 million tons of OPF, accounting for 53% of the total palm biomass (Goh et al., 2010; MPOB 2009). Thus, OPF is a solid agro waste which is abundantly available on oil palm plantations (Goh et al., 2010). A study from Sudin (1996) showed that fibre extracted from the OPF can be used as wood aggregate in the manufacture of wood fibre cement composite. Oil palm fronds and oil palm trunks used to be burned but environmental concerns led to banning the practice in the 1990s. Now they are usually left on the ground to decompose and fertilize the soil (Lim et al., 2000). However, present practice at oil palm plantation is to leave OPF as mulching agent on site (Allah Wadhoyo, 2014) but they cannot be stacked in more than two layers around the tree or they attract harmful insects (Prasertsan et al., 1996). A more value added application for OPF could be the development of natural fiber reinforced composite to substitute steel or polymers which are traditionally used in reinforced cement board (Mohr, 2005) and for over one century (Liu, 2010). Youngquis (1996) investigated agricultural waste such as rice husk, coconut coir, peanut shell and bagasse to produce fibre cement boards and reported no adverse effect of these materials on Portland cement hardening and board strength. Numerous studies evaluated the effectiveness of various additives such as calcium chloride (CaCl₂), magnesium chloride (MgCl₂), aluminium sulphate (Al(SO₄)₃) and sodium silicate (Na₂SiO₃) in enhancing the hardening reactions of cement in the presence of lignocellulose materials (Olemufi, 2012; Rahim, 1991; Faranak, 2015). Reaction of Na₂SiO₃ give very quick reaction with calcium ions (Ca²⁺) and good properties that allows silicate to be used as a cement accelerator (Mike, 2003). Compared with other available accelerators such aluminum chloride, femc chloride and diethanolamine, aluminium sulphate (Al(SO₄)₃) is considerably lower in price while effectively enhancing cement board mechanical properties (Rahim, 1990). The objective of this research paper is to develop an eco-friendly OPF cement board from agricultural waste for application in the south-east Asian building industry.

2 Experimental Section

2.1 Materials

The dried OPF was obtained from a private plantation nearby Universiti Kebangsaan Malaysia (UKM) in Bangi. The OPFs were selected from 15 to 20 years old oil palms and transported to MPOB for subsequent processing. Leaflets were removed from the fronds. Only the petiole part was used in this study (Figure 1)
Plates 1 (a) shown the collected dried oil palm frond that was crushed and these particles produced using Hammer mill machine. The average length of the OPF particles were 2 cm to 3 cm as shown in Plates 1 (b). The moisture content of dry OPF particles was 13%.

Plate 1: (a) Dried OPF particles  (b) Length of OPF particles

Eco-friendly Portland cement type as well as additives aluminium sulphate (Al₂(SO₄)₃) and sodium silicate (Na₂SiO₃) were mixed well in order to increase the bonding and hardness of the cement board.

2.2 Mixture Proportions

The mixture proportions of OPF cement board are shown in Table 1. Three different ratios of OPF to cement; 1:3.50 (B1), 1:4.00 (B2) and 1:4.50 (B3) with a targeted density of 600 kg/m³ were prepared.

<table>
<thead>
<tr>
<th>Board No.</th>
<th>OPF (g)</th>
<th>Cement (g)</th>
<th>Al₂SO₄ (g)</th>
<th>Na₂SiO₃ (g)</th>
<th>H₂O (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>441.78</td>
<td>1368.35</td>
<td>205.28</td>
<td>410.51</td>
<td>214.31</td>
</tr>
<tr>
<td>B2</td>
<td>397.18</td>
<td>1405.95</td>
<td>210.89</td>
<td>421.79</td>
<td>204.21</td>
</tr>
<tr>
<td>B3</td>
<td>360.79</td>
<td>1436.78</td>
<td>215.51</td>
<td>431.04</td>
<td>195.92</td>
</tr>
</tbody>
</table>

2.3 OPF cement board fabrication process

The research using laboratory experimental methods carried out in the Wood Industry Workshop in Universiti Teknologi Mara, Pahang. The OPF cement boards were prepared as follows. All the material in table 2 was weighed and then placed into the cement mixer and combined with additives that were poured slowly and mixed uniformly at moderate speed for ten minutes. Next, the mixture was uniformly distributed in a mold (340mm × 340mm × 25mm), which was then placed on a metal plate and covered with a plastic sheet to prevent the board from sticking to the plate. Another plate was placed on the top of the mat and a pressure of 100 kg/cm² applied for three minutes. For primary curing to occur, the board was placed in a conditional chamber for 24 hours WITH 65°C. Subsequently, the board was then removed from the mold and placed in the curing tank at room temperature of 27°C and consistent relative humidity of 60% for 14 days for final curing of the boards. The cured boards were cut into test pieces as detailed in MS 934: 1986. Each batch of materials was prepared for two replicate boards.

2.4 Testing

Sample preparation and measurement of the mechanical and physical properties were carried out according to MS 934:1986 Specification of wood cement board. The MoR, MoE and tensile strength were tested by using Universal Testing Machine INSTRON 5569. While for thickness swelling and water absorption was measured after being immersed in water for 24 hours. Samples for all tests were cut based on the standard requirement. The thermal properties of OPF cement boards was determined using thermal properties
analyser Quickline TM-30/Anter Corp., as showed in plates 2 below that provides result of thermal conductivity (k), the thermal diffusivity (α) and the calorific capacity (Cp).

Plate 2: Thermal properties analyser: (a) TM–30; (b) probe; (c) OPF cement board sample

Scanning electron microscopy (SEM) SUI510 Hitachi was used at accelerating voltage of 3kV for microstructural observation. The images were obtained through microscopic investigation. Square sample were cut 40mm × 40mm and cleaned using blower. No coating was required for these sample.

3 Results and Discussion

OPF cement boards of three different OPF cement ratios were prepared and analysed for MoR, MoE, tensile strength, thermal conductivity, thickness swelling, water absorption after 24 hours of immersion in water (Table 3) and morphology.

Table 3: The mechanical and physical properties of OPF cement board produced at different OPF cement ratios

<table>
<thead>
<tr>
<th>Board no.</th>
<th>OPF cement ratio</th>
<th>Density of board (kg/m³)</th>
<th>MOR (MPa)</th>
<th>MOE (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Thickness Swelling (%)</th>
<th>Water Absorption (%)</th>
<th>Thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1:3.50</td>
<td>*660±00</td>
<td>±18.8</td>
<td>±2569.0</td>
<td>±0.52</td>
<td>±0.48</td>
<td>±35.02</td>
<td>±0.099</td>
</tr>
<tr>
<td>B2</td>
<td>1:4.00</td>
<td>*632±28</td>
<td>±14.3</td>
<td>±2431.7</td>
<td>±0.57</td>
<td>±0.52</td>
<td>±33.59</td>
<td>±0.122</td>
</tr>
<tr>
<td>B3</td>
<td>1:4.50</td>
<td>*604±56</td>
<td>±12.3</td>
<td>±2362.6</td>
<td>±0.63</td>
<td>±0.65</td>
<td>±31.61</td>
<td>±0.128</td>
</tr>
</tbody>
</table>

Malaysian Standard MS 934

>1000 9.00 3000 >0.50 <2.00 NS <0.35

*Remark: Acceptable range is 600 kg/m³ with limit ±60 kg/m³ (INSTRON standard guideline)
*NS = not stated in MS 934

The results show that the OPF cement board density was closed to the targeted density of 600 kg/m³. Board density decrease linearly (R²=1) with increasing OPF cement ratio which may be explained by the factor affecting concrete density due to uninformed distribution of particle during fabrication process (Tarun, 1997). Similar finding have been reported by Joseph (2006) where the density of hardened cement decrease as the proportion ratio increase. In principle, the density decreased with increase of fibre content but procedural factors influencing to the result that potentially given inaccurate reading (Joseph, 2006). The MoR was greatest for ratio 1:3.50 was greater probably due to the larger amount of OPF particles. Similar findings were reported by Orefice et al. (2001) who proposed that particles with larger values of aspect ratio led to large elastic and rupture but lower level of failure. All three boards satisfy the requirements of the Malaysian Standard MS 934 which stipulates a minimum bending strength of 9 MPa for boards.
Results are in agreement with Zakiah and Fadzil (2014) who obtained a bending strength of 10 MPa for a kenaf cement board of density 720 kg/m$^3$.

In addition, similar trend was attained for MoE where OPF cement board with ratio 1:3.50 indicates higher result 2569 MPa compared to the other two board 2432 and 2363 MPa (Figure 2). These results also considered acceptable as they satisfy the strength properties of MS Standard specification which has minimum requirement of 3000 MPa for 1000 kg/m$^3$. But in this study, the board density was around 600 kg/m$^3$ and the analysis shows the MoE was approximately 2569 MPa near to achieve 3000 MPa. Means that, this present study was proved by having low density board was achieved better modulus elasticity result. Similar with Oyagade (1989), resulted that board with low density was linearly and positively related to bending properties including MoE and MoR of cement bonded particleboard when cement/wood ratio was held constant.

![Figure 2: MOE vs. different OPF cement ratio](image)

The results of tensile strength of OPF cement board also increased with increase ratio and all the boards met the specification of the Malaysian Standard MS 934 where it should be more than 0.50 MPa. The increase trend can be seen starting from 0.52 MPa to the higher ratio of OPF cement board 1:4.50 has optimum tensile strength of 0.63 MPa. This indicates that the higher the additive amount, the higher bending strength of the OPF cement boards. According to the Jitendra (2013), the factor of reduction in tensile strength happen with addition of particle because of poor adhesion during manufacturing.

The analysis of thickness swelling (TS) and water absorption (WA) after 24 hour immersion in water showed a decrease trend with the increase OPF ratio in the mixture which were 0.65, 0.52 and 0.48% for TS respectively. It can be related to the higher proportion of cement, the lower moisture content, thickness swelling and water absorption (Asasutjarit 2007). Furthermore, Semple and Evans (2007) argue that thickness swelling is highly dependent on particle geometry. It increases with increasing particle thickness and decreasing particle length. The use of thicker particles results in greater heterogeneity and more irregular open board surface which is more easily penetrated by water. All of the OPF cement board met the Malaysian Standard MS 934 requirements below 2%. For water absorption, the result showed board 1 have highest percent of WA which are 35.02%.
followed by 33.59% and 31.61% respectively. It can be related to the lesser cement value, the greatest absorption occurred. Rudy and Andriaty (2012) was explained that wood particles have greatest absorption among board materials when exposed to water but clamp load may play dominant role in reducing this effect owing to more cement matrix coverage by pressure, leading to blocking the flow of water into wood particles. Higher clamp load results higher density and increasing cement values decreased water absorption same results by Aggarwal (1995). There is no requirement for maximum water absorption in MS 934.

![Figure 3: Thickness swelling and water absorption result](image)

### 3.1 Thermal conductivity

The average thermal conductivity for three different ratio OPF cement board was examined in table 4 below.

<table>
<thead>
<tr>
<th>Board No.</th>
<th>Test specimen thickness</th>
<th>Thermal conductivity- k (W/m·K)</th>
<th>Calorific Capacity- Cp (J/m³·K)</th>
<th>Thermal diffusivity - α (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 (1:3.50)</td>
<td>50 mm</td>
<td>0.099</td>
<td>329000</td>
<td>0.303 x 10⁻⁶</td>
</tr>
<tr>
<td>B2 (1:4.00)</td>
<td>50 mm</td>
<td>0.122</td>
<td>345000</td>
<td>0.356 x 10⁻⁶</td>
</tr>
<tr>
<td>B3 (1:4.50)</td>
<td>50 mm</td>
<td>0.128</td>
<td>386000</td>
<td>0.370 x 10⁻⁶</td>
</tr>
<tr>
<td>Requirement MS 934</td>
<td>&lt; 0.35</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

To be building material, cement boards should have heat resistant capability. This project examined the heat resistant capability of cement boards by using the thermal conductivity in accordance with Malaysian Standard MS 934 and the results are shown in Table 4. For OPF cement boards, the values of thermal conductivities was within 0.099 and 0.128
W/m.K, lesser than standard requirement. The decreasing trends of thermal conductivity k value showed that the more natural particles in the board, produce better thermal performance. Where the slower heat will move across a material. And generally, light materials are better insulators than heavy materials, because light materials often contain air enclosures (Clear, 2010). Therefore, it can be said OPF cement board have desirable heat resistant capability. This present study was proved by used OPF waste, it was able to produce lightweight cement board with better strength, tensile and thermal properties.

3.2 Scanning Electron Microscopy (SEM) imaging observation
The SEM scanned a high energy electron beam across the surface of a specimen and measured the interaction between the OPF particles and the Portland cement. In order to assess the effect of the board, SEM micrographs were taken from the three central part of each samples. Role of dispersion of particle and bonding with additives can be seen easily from SEM.

![SEM images of OPF cement board with ratio a)1:3.5, b)1:4.0, c)1:4.5](image)

Figure 4: SEM images of OPF cement board with ratio a)1:3.5, b)1:4.0, c)1:4.5

The SEM micrograph of the OPF cement board made with different mixture ratios 1:3.5, 1:4.0 and 1:4.5 are shown in Figure 4 (a-c). From the images it can be seen that the smaller the OPF:cement ratio the more porous the board. While additional quantity of Portland cement in fabrication process increased the uniform structure as shown in Figure 4c. The length and quantity of particles itself was plays important role and give influence to increase the mechanical properties of the board (www.virginia.edu). This is in agreement with earlier studies by Jitendra (2013) were observed the state of dispersion of coconut shell particles and amount of coir fibre into the resin matrix plays a significant role on the mechanical properties of the composite. Overall, all the OPF particles were coated well with cement.

4 Conclusion
The purpose of this project is to determine the mechanical and physical properties in the production of low density oil palm frond (OPF) cement board especially for the application in wall for building industries. Based on the results of the study, the following conclusion can be reached.

- The trend for the density value of the OPF cement board is decreased but still in an acceptable range 600 kg/m³.
The bending strength or Modulus of Rupture (MoR) of 1:3.50 ratio OPF cement board had higher result 18.8 MPa, compared to the boards with ratio 1:4.00 and 1:4.50.

All three OPF cement boards can be considered to be acceptable boards that satisfied the strength properties of the Malaysian Standard MS 934 because more than 9 MPa for MoR value and near to 3000 MPa for MoE specification.

All boards met tensile strength specification which optimum requirement for MS 934 is 0.5 MPa. The amount of chemical additives give influence to the internal bond tensile strength and this indicates the higher tensile strength is at board ratio 1:4.50; 0.63 MPa.

The OPF cement board has a significant effect of thickness swelling and water absorption. The higher the content of Portland cement in board, the lower the TS and WA.

The thermal conductivity of these three OPF was based on specification MS 934; which was lower than 0.35 W/m.K as required. Board 1 with ratio 1:3.50 had a lowest thermal conductivity and properties of 0.099 W/m.K.

SEM analysis showed that the board that have greater quantity of cement used during production; B3 1:4.50 resulted the uniform micro pores and structure.

It can be concluded that OPF agriculture waste has a potential to be used as a value-added natural material in bio-composite building material to produce wall and multipurpose cement board in future.

Acknowledgements
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APPLICATION OF POWER INTERRUPTER (PI) IN CONVENTIONAL SPLIT UNITS AIR-CONDITIONER

Mohd Mawardi Hussain1, Karl Wagner2 & Aloysius Decruz3

1 University Kuala Lumpur, MICET, 78000 Alor Gajah, Malaysia, and University of Applied Science Rosenheim, 83024 Rosenheim, Germany, mawardihussain@gmail.com
2 Universiti Kuala Lumpur, UBIS, 54000 Kuala Lumpur, Malaysia, karlwagner@unikl.edu.my
3 Universiti Kuala Lumpur, MFI, 43650 Bandar Baru Bangi, aloysius@unikl.edu.my

Abstract: Power interrupters (PI) for conventional, non-inverted split air-conditioning units are innovative devices designed to reduce energy consumption at low investment cost while at the same time providing higher level of thermal comfort for users. In Malaysian urban areas, about 85% of the existing residential houses are made of bricks. These brick houses require air-conditioners to cope with Malaysian humid tropical climate. Air-conditioners consume the highest percentage of electricity in residential houses followed by fridges, lighting and other household appliances. This study aims to compare the effectiveness of PI with the conventional remote control for electrical energy saving of a conventional non-inverted split air-conditioning unit. The purpose of the PI is to automatically detect the preset temperature once it is set at the ON and OFF button. Hence, the air conditioner does not work all the time but only within the boundaries of the preset temperatures. Data on temperature, relative humidity, and energy consumption were collected and analyzed. The results show that PI is more effective in controlling the non-inverter type conventional split unit air-conditioning system compared to the typical conventional remote control by helping to decrease the indoor room temperature and relative humidity to the MS1525:2007 thermal comfort zone respectively while also reducing energy consumption by 22%. The payback time for the PI was estimated to be 6 months.

Keywords: Power Interrupters; Building Automation; Energy saving; Conventional Non-inverted split unit Air conditioning; Energy Efficiency.
1 Introduction

The total number of households with air-conditioning in Malaysia has dramatically increased from 13,000 in 1970 (0.8%) to 229,000 in 1990 (6.5%) and 775,000 in 2000 (16.2%) (Kubota 2011). The yearly electricity consumption caused by air conditioning was recorded the largest amount among others household appliances (Kubota 2011).

The main focus of this study is to identify the energy saving potential of the power interrupter (PI) device when applying it with the conventional split unit air conditioning type. The PI device is expected to provide precise thermal comfort to the building occupants compared to systems that do not use the PI with the conventional split unit air conditioning type. The usage of the inverter split unit air conditioning type was excluded because people who already invested in conventional split unit air conditioning system are not likely to replace their unit particularly if an alternative way of saving electricity and thus cost can be proven.

2 Methodology

The energy saving of conventional non-inverter air conditioning split unit type (LG, HS-C0966ZRLO retrofitted with a PI Universal Thermostat device (ELV, Conrad) where determined while maintaining the indoor room temperature and relative humidity in accordance with MS1525:2007.

2.1 Site location and data collection

A one bed room in a residential, double storey terrace house at No. 29, Jalan Sunway 1/2A Bandar Sunway Semenyih, Semenyih (Selangor, Malaysia), (latitude: 2.9659097000, Longitude: 101.8236063000) was chosen for this study. The averages outside dry and wet bulb temperatures were 32°C and 29°C, respectively, while the average outside air relative humidity was 80%.

<table>
<thead>
<tr>
<th>System</th>
<th>Data type</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Unit AC System without Power Interrupter</td>
<td>Room Indoor Temperature °C, Room indoor Relative Humidity RH, Air Cond Electricity consumption kWh</td>
<td>3 days (15 hours / day) 7am to 10pm</td>
</tr>
<tr>
<td>Split Unit AC System with Power Interrupter</td>
<td>Room Indoor Temperature °C, Room indoor Relative Humidity RH, Air Cond Electricity consumption kWh</td>
<td>3 days (15 hours / day) 7am to 10pm</td>
</tr>
</tbody>
</table>

VOLTCRAFT DL-141TH Data Logger (figure 1) is used to get the real time indoor room temperature and relative humidity conditions. One data logger used to record complete data of indoor room temperature and indoor room relative humidity inside of the bedroom (Test room) at the double storey terrace house throughout the study.
When all the data is recorded, the data will be sync transferred and downloaded in the software named RHT20. RHT20 will display the complete data on temperature and relative humidity data in graphical and spreadsheet documents to produce and develop the comparison graphs by superimposing the interior data of relative humidity and temperature.

To record the complete data on the use of energy, the instrument called power data logger or e2 Wireless Power Electricity Monitors was used. The power logger has three parts that are sensor, wireless display and transmitter. Sensor has been attached to the life wire of the Split unit Air Conditioner and connected to the transmitter. Wireless display that will record all the readings will be placed near the transmitter as shown in figure 2.

2.2 Building plan and cooling system installed

Figure 3 shows the house Air Conditioner layout plan. Figure 4 shows the location of Split unit Air Cond Condenser installed and Figure 5 shows the location of the Split unit Air Conditioner evaporator. The indoor temperature, relative humidity and also Split unit Air Conditioner energy consumption data were taken in this bedroom R1 marked red at the second floor of the house. Table 3 describes the Split unit Air Conditioner (non-inverter) system specification use in this experiment.
Figure 3: Second floor House / bed room AC layout plan

Table 2: Split Unit Air Cond system location

<table>
<thead>
<tr>
<th>Legend</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Condenser 1</td>
</tr>
<tr>
<td>E1</td>
<td>Evaporator 1</td>
</tr>
<tr>
<td>R1</td>
<td>Room</td>
</tr>
</tbody>
</table>

| Area    | 9.45m²              |
| Height  | 3.30m               |

Wall Type: Brick Wall

Figure 4: Condenser installed at outside bedroom
Table 3: Split Unit Air Cond (Non-inverter) system Specification

<table>
<thead>
<tr>
<th>Item</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company/Brand</td>
<td>LG</td>
</tr>
<tr>
<td>Type</td>
<td>Split Room Air Conditioner</td>
</tr>
<tr>
<td>Model</td>
<td>HS-C0966ZRL0</td>
</tr>
<tr>
<td>Electrical Power</td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>0.85kW</td>
</tr>
<tr>
<td>Fan at Condenser</td>
<td>35W</td>
</tr>
<tr>
<td>Fan at Evaporator</td>
<td>15W</td>
</tr>
<tr>
<td>Cooling Power</td>
<td>9,000Btu/h or 2.63kW</td>
</tr>
<tr>
<td>EER: (Cooling power, W/ Compressor power, W)</td>
<td>3.1</td>
</tr>
</tbody>
</table>

2.3 Power Interrupter Device

The power interrupter PI works like a thermostat. The basic function of these device is to turn the conventional split unit Air Conditioner ON and OFF at a pre-setting temperature. It is an adjustable differential set point temperature setting. During the testing period of the Power Interrupter. The PI differential temperature set point setting is 0.5 Celsius (ON: 24.5 Celsius, OFF: 24.0 Celsius) while the conventional split unit Air Conditioner remote control was set at the lowest available Air Conditioner split unit temperature set point setting that was 18 Celsius. The PI device works at its best if the user prefer to keep the indoor air temperature at a constant level at all times and are away from home for several hours each day and want to save the energy use for cooling at the same time. The purpose of this device is to maintain a constant indoor air temperature in a home or building. The device can easily be set to a certain temperature when leaving the home or building each day or also can adjust it at night when sleep time. So, occupant will feel the better thermal comfort inside the building without the need to make frequent adjustments in temperature compared to the air-conditioning system without this device. The Power interrupter ELV Universal Thermostat from Conrad manufacturers was used for this study. Figure 6 shows the Power Interrupter ELV Universal Thermostat device was connected between Split unit
Air Cond and the Home electrical supply socket with the thermostat sensor attached at the bedroom wall near the occupant sleeping bed.

Figure 6: Power Interrupter ELV Universal Thermostat device was installed inside bedroom

2.4 Conventional Air Conditioner Remote Control

When testing the Air Conditioner without PI device. The normal conventional remote control device (figure 7) only turns ON the conventional split unit Air Conditioner at its pre-setting temperature. Besides, it is not an adjustable differential temperature setting like PI. During the without PI testing period the conventional Air conditioner remote temperature set point was set at 24 Celsius.

Figure 7: Conventional Split Unit Air Conditioner remote control

3 Results and Discussion

One of the major reasons for this experiment is analysing the results of the comparison between Split unit Air Conditioner with PI and without PI. The comparison criteria are: comparison of indoor temperature between Split unit Air Conditioner with PI and without PI; comparison of indoor relative humidity between Split unit Air Conditioner with PI and without PI; comparison of Six sigma spread of temperature Split unit Air Conditioner with PI and without PI; and comparison of electricity consumption between Split unit Air Cond with PI and without PI. Three-day data measurements were taken in between June to December 2016, at a 2-storey intermediate terrace house located at Bandar Sunway Semenyih, Semenyih, Selangor Malaysia. The average outside dry bulb temperature was 32°C and outside wet bulb temperature was 29°C. The average Relative humidity was 80%. The collected data were analysed using Microsoft Office Excel and Minitab 15 software. The benchmark of temperature control is based on the comfort cooling zone MS1525:2007 Malaysian Code of practice on energy efficiency that is in the range of 23
Celsius to 26 Celsius. The results of the comparative case studies is discussed in this section.

3.1 Comparison of indoor temperature (°C) between Split Unit Air-Cond with Power Interrupter & without Power Interrupter

Figures 8 to 10 illustrate the three-day comparison of indoor Temperature (°C) between Split unit Air Conditioner with Power Interrupter and Split unit Air Conditioner without Power Interrupter. Both data were collected every 15 minutes for 15 hours from 7am to 10pm. Day 1 data for Split unit Air-Cond without Power Interrupter was taken on 20/08/2016 while with Power Interrupter on 04/09/2016. The Day 2 data for Split unit Air Conditioner without Power Interrupter was taken on 14/08/2016 while with Power Interrupter on 09/10/2016 and lastly, the day 3 data for Split unit Air Conditioner without Power Interrupter was taken on 21/08/2016 while with Power Interrupter on 06/11/2016. Split unit Air Conditioner with Power Interrupter remote control set point was set at 24 Celsius while Power Interrupter device set point was set at 24 Celsius OFF Temperature and 24.5 Celsius ON Temperature.

3.2 Day 1 Comparison Indoor temperature (Celsius) of Split unit Air-Conditioner with Power Interrupter and without Power Interrupter

Based on the Temperature (Celsius) – temperature reading (Index) series chart (Figure 8) for the first 10th temperature readings. It was shown that the Air Conditioner is starting to cool the room. The Split unit Air Conditioner with PI reaches its set point temperature at 24 Celsius then it was constantly located at the temperature of 24 Celsius to 24.5 Celsius until end of the Split unit Air Cond operating hours room last temperature reading at 60th readings. Meanwhile, The Split unit Air Conditioner without PI kept cooling until it reached 23 Celsius which was 1 Celsius lower than the AC remote control set point temperature value of 24 Celsius. Then, after 24th temperature readings the temperature increased to the Split unit Air Conditioner remote control set point temperature at 24 Celsius. After 44th temperature readings the temperature of the room cooled down further and fell below than 24 Celsius until it reached 23 Celsius at the 56th temperature readings.

![Figure 8: Day 1 Comparison Indoor Temperature of Split Unit Air-Cond with PI and without PI](image-url)
3.3 Day 2 Comparison Indoor temperature (°C) of Split unit Air-Cond with Power Interrupter and without Power Interrupter

Based on the Temperature (Celsius) – temperature reading (Index) series chart (figure 9) for the first 10th temperature readings. It was shown that the Air Conditioner is starting to cool the room. The Split unit Air Cond with PI reaches its set point temperature at 24.2 Celsius then it was increased to the 25.8 Celsius. After the 24 temperature reading (index), the temperature is back constantly at 24.5 Celsius and 25 Celsius until end of the Split unit Air Conditioner operating hour’s. The Split unit Air Conditioner without PI keep cooling until it was reaches 24 Celsius. Then, it increased to 25.7 Celsius and constantly stays there until after 48th temperature readings it cools down to 24 Celsius and keeps cooling down until end of the Split unit Air Conditioner operating hour’s room last temperature reading at 60th readings. From this chart we can see that the Split unit Air Conditioner with PI the room temperature is constantly not too far from the 24 Celsius desired Set point temperature while the Split unit Air Conditioner without PI were not constant and deviating more times from the 24 Celsius desired set point temperature.

Figure 9: Day 2 Comparison Indoor Temperature of Split Unit Air-Cond with PI and without PI

3.4 Day 3 Comparison Indoor temperature (°C) of Split unit Air-Conditioner with Power Interrupter and without Power Interrupter

Based on the Temperature (Celsius) – temperature reading (Index) series chart is as shown in Figure 10 for the first 6th temperature readings. The Split unit Air Conditioner with PI reached its set point temperature at 24°C then it became constant at the temperature of 24°C to 24.5°C until end of the split unit Air Conditioner operating hours room last temperature reading at 60th readings. Meanwhile, The Split unit Air Conditioner without PI cooled until reached 25.2°C which was 1.2°C more than the split unit Air Cond remote control set point temperature value of 24 Celsius. Then, it stayed constant at the temperature of 25.2 Celsius and 25.8 Celsius until 42nd temperature readings, the temperature dropped to 23 Celsius until end of the Split unit Air Conditioner operating hours room last temperature reading at 60th readings. From this chart we can see that the Split unit Air Conditioner with PI the room temperature was constant at its ON and OFF temperature that was not too far from the 24°C desired set point temperature while the
Split unit Air Conditioner without PI was not constant and deviated most of the times from the 24°C desired set point temperature.

3.5 Comparison of indoor relative humidity between Split Unit Air-Cond with Power Interrupter & without Power Interrupter

Figures 11 to 13 illustrate the three-day comparison of room indoor relative humidity (%) between Air Conditioner with Power Interrupter and without power Interrupter whose both data were collected every 15 minutes for 15 hours from 7 am to 10 pm. The benchmark of relative humidity control is based on the comfort cooling zone MS1525:2007 Malaysian Code of practice on energy efficiency that is 55 RH (%) to 70 RH (%).
It can be concluded that Power Interrupters helped the Split Unit Air Conditioner to control the humidity up to 9 times more precisely in the range of MS1525 relative humidity cooling comfort zone compared to Split Unit Air Conditioner without Power Interrupter. The Application of Power Interrupter increased the occupant's comfort while in the room.

3.6 Comparison of six sigma spread of temperature Split Unit Air Conditioner with Power Interrupter & without Power Interrupter

Below figure 14 is the result of the daily average indoor temperature & standard deviation spread comparison of split unit Air Conditioner system with PI and without PI for 15 hours per day for 3 different days of experiment.
3.7 Split Unit Air Conditioner system without Power Interrupter PI

Desired set point temperature is 24°C. Conventional Split Unit Air Conditioner remote control set point temperature was set to 24 Celsius. Though the Air Conditioner remote control was set to 24°C. The indoor room temperature was not at 24°C as the pre-set point desired temperature all the time. The average indoor room temperature for day one, two, and three was at 25.3°C, 24.9°C and 25.3°C respectively. The indoor room temperatures deviate far from the pre-set temperature. This means, the conventional Air Conditioner remote control system is not so efficient in controlling the indoor room temperature towards its desired set point temperature.

3.8 Split Unit Air Conditioner system with Power Interrupter PI

Power Interrupter desired set point temperature was set to 24°C OFF and 24.5°C ON. Though, the conventional Split Unit Air Conditioner remote control set point was set to the lowest set point possible 18°C. The indoor room temperature was always at 24°C to the 24.5°C as the pre-set point desired temperature range all the time. The average indoor room temperature for day one, two, and three was at 24.6°C, 24.9°C and 24.5°C respectively. The indoor room temperatures not deviate far from the pre-set temperature 24°C OFF and 24.5°C ON compared to the Split Unit Air conditioner system without PI. This means, the Power Interrupter control system is better in controlling the indoor room temperature in the desired temperature set point range compared to the conventional remote control for Split Unit Air Conditioner without PI.

Figure 14: Daily average Indoor Temperature and Standard Deviation Spread Comparison of Split Unit Air Conditioner system with PI & without PI
3.9 Comparison of electricity consumption between Split Unit Air-Cond with Power Interrupter and without Power Interrupter

A comparison of energy consumption was among the important 3 days comparison done throughout this study. In total, over 3 days with Air Conditioner operating for about 15 hours per day, the total electricity consumption for air conditioning with Power Interrupter was 24.2315 kWh while without Power Interrupter was recorded at 29.0564 kWh. Total Energy reduction or in other words energy savings over three days was 4.8249 kWh with around 17% of energy reduction. Due to that, estimated monthly housing electrical bills in Ringgit Malaysia if Using Power Interrupter can be reduced around RM16.12/month with the percentage of saving of 22% from the total of RM 73.85/month without using Power Interrupter. With the saving of RM16.12/month, the payback period of owning the Power Interrupter is just 6.2 months which is less than one year for the RM100 price for each power interrupter device. Figure 15 is a bar chart with its standard errors (SE) bar shows the average hourly air conditioner electrical energy consumption with or without PI in 15 hours per day for the three days experiment.

![Average hourly Air Conditioner electrical energy consumption with and without PI in 15 hours / day for three days experiment](image)

Figure 15: Average hourly air conditioner electrical energy consumption with or without PI in 15 hours per day for three days experiment.

3.10 Comparison of Electrical Carbon equivalent emission (kg.CO\textsubscript{2}/kwh) between Split unit Air Cond with Power Interrupter and Split unit Air Cond without power interrupter.

The Malaysia electricity-specific emission factors for each 1 kWh produce is equal to the 0.749 kg.CO\textsubscript{2}/kWh (Brander et al., 2011). Over 3 days with Air Cond operating for about 15 hours, the total electricity consumption for air conditioning with Power Interrupter was 24.2 kWh while without Power Interrupter was recorded at 29.1 kWh. The total carbon footprint produced when using Split unit Air Cond with power interrupter was 18.2
kg.CO$_2$/kwh lower than Split unit Air Cond without power interrupter was 21.8 kg.CO$_2$/kwh, which was 17% of Carbon emission reduction. Apart of electricity energy saving from the application of power interrupter, the usage of power interrupter also contributed to the preservation of the environment by lessening carbon emission and it can be claimed as one of the green building initiatives.

4 Conclusions

The Power Interrupter is the perfect device in helping the conventional split unit Air Cond (Non-inverter) type in reducing its energy consumption. The experiment succeeded to show that the Power Interrupter helps the conventional split unit Air Cond (Non-inverter) type to reduce the energy consumption by 4.82 kWh for 3 days of 15 hours/day operation. Due to that, estimated monthly housing electrical bills in Ringgit Malaysia if Using Power Interrupter can be reduced around RM16.12/month with the percentage of saving of 22% from the total of RM 73.85/month without using Power Interrupter. With the saving of RM16.12/month, the payback period of owning the Power Interrupter is just 6.2 months which is less than one year.

The experiment also succeeded to show that Conventional Air conditioning split unit type (Non-inverter) with Power Interrupter device helps to decrease the indoor room temperature and relative humidity significantly at better thermal comfort level in the range of MS1525:2007 Malaysian standard energy efficiency code of practice for non-residential building compared to the Conventional Air conditioning split unit type (Non-inverter) without Power Interrupter device.

The indoor Temperature of Split unit Air Cond with Power Interrupter reached its set point temperature at 24°C then it stayed constant at the temperature of 24°C to 24.5°C until end of the Split unit Air Cond operating hours room last temperature reading at 60th readings.

Meanwhile, the indoor temperature of Split unit Air Cond without Power Interrupters was not consistently located at its set point temperature of 24°C but it kept cooling until it reached outside the 24°C temperature set point.

Furthermore, Power Interrupter helps the Split Unit Air-Cond to control the humidity up to 9 times more precisely in the range of MS1525:2007 relative humidity cooling comfort zone compared to Split Unit Air-Cond without Power Interrupter. The Application of Power Interrupter helps increase the occupant's comfort staying in the room.

The indoor room temperatures deviate far from the conventional remote control pre-set temperature 24°C for the Split Unit Air Conditioner system without PI. This means, the conventional Air Conditioner remote control system was not so efficient in controlling the indoor room temperature towards its desired set point temperature. For the Split Unit Air Conditioner System with PI. The indoor room temperatures did not deviate far from the pre-set temperature 24°C OFF and 24.5°C ON compared to the Split Unit Air conditioner system without PI. This means, the Power Interrupter control system is better in controlling the indoor room temperature in the desired temperature set point range compared to the conventional remote control for Split Unit Air Conditioner without PI.

Apart from electricity energy saving from the application of power interrupter, the total carbon footprint produced when using Split unit Air Cond with power interrupter was 18.2 kg.CO$_2$/kWh lower than Split unit Air Cond without power interrupter 21.8 kg.CO$_2$/kWh by the 17% of carbon dioxide emission reduction. The usage of power interrupter also
contributes to the preservation of the environment by lessening the carbon emission and it can be claimed as one of the green building initiatives.

Acknowledgements
The principal author would like to thank University Kuala Lumpur MICET for providing him with the measurement tools and guidance through the course of his project; and MARA, for the financial aid they have given him for his degree.

References


Abstract: The main aim of this research is to use empty fruit bunches (EFB), a by-product of the palm oil industry, as an environmentally friendly building material in non-load bearing walls. EFB fibres are non-toxicity, mitigate global warming, are of low density and possess acceptable mechanical strength properties. However, original EFB fibres suffer from poor moisture resistance, low durability and poor fire resistance. This study aims to utilise the advantages of EFB fibre while minimising its drawbacks by mixing it with inorganic substances like cement, aluminium sulphate (Al₂(SO₄)₃) and sodium metasilicate (Na₂SiO₃). The thermal conductivity of a 300 mm x 300 mm x 80 mm sample was found to be 0.118 W/m.K at a density of 450 kg/m³. This material is fire retardant after being exposed to 2-hour fire test with the highest temperature of 1100°C. It also resists attacks of a subterranean and a drywood termite species according to ASTM D3345-74. Mold growth was studied as detailed in ASTM C 1338-08 and found to be reduced in mixture materials. This should be a potential future insulation material to be implemented in Malaysia as the alternative solution to adapt to environmental crisis and green technology development.

Keywords: Empty Fruit Bunches (EFB), Insulation, thermal conductivity, waste material, lightweight material, building material.
1 Introduction
Advancement in Science and Technology in this century intensifies efforts in the many interesting designs and creations particularly in the building construction industry. Many products are now being actively produced by using grown crops waste in this country. This level of progress has achieved very encouraging results to broaden the country’s development. Malaysia is developing in line with other developed countries in producing its own commodity by using its own source from the recyclable output input in addressing stockpiles and waste pollution to the environment. To produce a new product from waste material, will have a constructive consequence to the country, especially in terms of modernizing new products. Wastes from oil palm can be used a value added product advantageous to the country. With the advancement of Malaysia in high technology, research centres like Malaysian Palm Oil Board (MPOB) and other institutions, in the country have adequate resources that can provide a great opportunity to other parties in any field to produce new products. Products from waste material can be manufacture with efficient cost and can be utilised by all levels of society because of their availability, especially in Malaysia. Waste material such as empty fruit bunch (EFB) fibre is accessible in Malaysia’s climate and vast areas of land for oil palm, which are easily produced throughout the country due to high number of production every year. According to (Loh et al., 2011) Malaysia is the main country in producing of Oil Palm, and wastes from Oil Palm was expected about 46 million tons every year, with 30 million tons for biomass from its oil palm trunk (OPT), its frond (OPF) and EFB). EFB id produced when the oil extract is taken from the palm kernel during the manufacturing process, where the EFB is shredded for refinement and separated from the oil palm fruit grafting to form fibre. It is then dried until it reaches the minimum level of internal water content. Since marketed insulation material, such as Rockwool, is expensive, this research suggests recyclable materials that could optimize the cost. The advantages of EFB fibre are biodegradability, reduced greenhouse emissions, non-toxicity, low density, and acceptable specific strength properties (Loh et al., 2011). Currently EFB is utilized with polypropylene (PP) to be used in automotive applications, Insulations and the manufacturing of mattress. However, according to (Joseph et.al, 2006), EFB have some disadvantages such as poor moisture resistance, low durability and poor fire resistance that need to be overcome in this study. According (Kolop et al., 2011) EFB is a unique material as it is non- hazardous, renewable and readily available at relatively low cost due to established technology to extract the fibres compared to other commercially available fibres.

2 Methodology of production
2.1 Raw Material
The oil palm empty fruit bunch (EFB) fibre is supplied by the MPOB agency; the manufacturer is located in Bangi, Malaysia. The fibre’s length should be approximately 20 -30 cm to make sure the bond is strong. Before the mixing process the fibre needs to be separated from each other to become single pieces. During the mixing process, all pieces of fibres are perfectly coated with cement. This phase of fibre is called long fibre. According to Jeyanthi (2012) long fibre are widely used due to their high specific strength, good damping capacity and corrosion resistance. This will ensure the product made will be long lasting due to its strength. Portland cement is used as a binder with conformed to MS 522: Part 1: 1989 with specific gravity of 3.15 (Kolop et al., 2011). Distilled water was used to mix an adhesive such as sodium metasilicate Na$_2$SiO$_3$. Sodium metasilicate is extensively used as a cost persuasive extender, allowing a higher ratio of water to cement. With supplementary water, the cement density diminishes and reduces the hydrostatic pressure, abbreviating lost circulation and fracturing the formation. From a cost aspect,
water is more cost-effective than neat cement. Sodium metasilicate minimize the mobility of water in cement. When they fluidity, the ions will respond with calcium ions from the cement to shape a calcium silicate hydrate gel. It is the calcium silicate hydrate gel that adequately ties up prodigious abundance of the sludge mix water without the consequential of free water. The cement remains homogeneous with no dissociation. Sodium metasilicate functional as a cement accelerator for reliable acceleration, it is essential that the metasilicate ion remain in solution before reacting with Ca+2 ions, or else premature gelling is likely to arise (Bested et al., 1996). Another chemical binder added together for better mixing is Aluminium Sulphate Al₂(SO₄)₃, which is also used to be in the mix with Sodium Metasilicate. An experiment by (Kan et al., 2013) showed that the addition of Aluminium Sulphate into the cement mix will shorten the setting time of the cement, it also can upsurge the drying shrinkage and revamp the early strength of the cast. However, it will undermine the late strength of cement and reduce fluidity. The addition of Aluminium Sulphate with micro research will change the morphology and point of Aluminium Sulphate distinctly.

Before the mixing process, the Fibre is disentangled to attenuate the loops of the EFB fibre with other materials during the mixing process. This is because of the range of long fibre’s diameter is between 50 -610 µm (Norhan, 2015) and it easily clots, thus the dry EFB fibre is soaked into water for one day to make it easy to mix with other binders in the mixing process. Framework is created for the better curing process with the first layer covered by non-woven fabrics with advantages like absorbency, liquid repellence, elasticity, stretch, softness, strength, flame retardancy, wash ability, thermal insulation, acoustic insulation, filtration, bacterial barrier and sterility. According to Lin et al. (2009), this material has to go through thermal pressing temperature until it reaches 200°C and has a low fibre contents of 50% and has 5 layers to access tensile strength, thermal conductivity 0.59W/m.K and limit the oxygen index to 35% (LOI).

In this research there are 3 samples provided at different expected densities which are 450kg/m³, 400kg/m³ and 200kg/m³ identified for lightweight building material as the range of lightweight material is 0 – 500 kg/m³. After 1 day of soaking in water, the EFB fibres are dried at 26 – 34°C ambient temperature, and the moisture content is measured using the Moisture content machine which bears 3.75%.

<table>
<thead>
<tr>
<th>Table 1.1: Proportion of ratio for the sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Proportion Ratio</td>
</tr>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1.2: Expected properties of each sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Density (kg/m3)</td>
</tr>
<tr>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>Mass</td>
</tr>
</tbody>
</table>

The manufacturing process proceeds when the raw material and other binders are mixed together with calculated ratio in the mixture machine to have a homogeneous mixture and the complete mixture will be poured into framework for the 28 days curing process. Before the curing process is initialized, the mixture is pressed with 1000 kg pressure to fix the gaps in between the samples to make them denser. The samples are placed in the curing chamber at 60°C for 24 hours. According to Klieger (1960) and Tepponen and Eriksson (1987), there are other advantages of curing concrete at temperatures of around 60°C. For example, there is reduced drying shrinkage and creep as compared to concrete cured at a lower temperature of 23°C or ambient temperature for the early stage of curing.
process. They recommended that the internal temperature of concrete does not exceed 70°C to avoid heat induced delayed expansion and undue reduction in the ultimate strength. After the pre-curing has been conducted for 1 day, the sample will be placed outdoor, exposed to ambient temperature with low level humidity to cure the bonding and the curing process for 28 days.

2.2 Method of Testing
After the curing process matures for 28 days, the sample is tested for the thermal properties test to obtain the thermal conductivity value of the sample. In the thermal conductivity test, the temperature is set between 30 – 32°C in order to mimic the actual temperature in Malaysia. According to Engel-Cox (2012), average annual dry bulk temperature in Malaysia is 27.6°C with a relative humidity of 83 %, cloud cover of 7 oktas, average wind speed of 1.2 m/s and global solar radiation of 16.4 MJ/(m²d).

2.2.1 Thermal Conductivity procedure
Thermal conductivity of the sample is measured using a surface probe type of QuicklineTM-30 (Fig.1.1). The probe implements a dynamic measurement method which can reduce the time of thermal conductivity and also the steady state condition by giving a shorter steady state from 10 - 15 minutes. Once the surface probe is in contact with the sample, constant current is then applied. The measurement is measured under room temperature of 20 - 24°C and the probe is placed in the middle of the sample to ensure good contact and to prevent measurement error.

2.2.2 Fire Resistance Procedure
Fire resistance needs to be tested in this research study to identify the extent of the material's ability minimize time of spreading flame to other parts of a building and to see whether the material is indeed fire retardant or not. The more time taken by flame to spread to other parts, the better is the product. The sample size 100mm x 100mm x 80mm thick is prepared following ASTM E119 standard with a sample density of 450kgm³. Two hours' time are needed for the test. In this test, there are two levels; the first level is burning process until the temperature reaches 600°C for and 1 hour, and the second level sees the burning process reaching 1100°C for an hour. Fire controlled by a gas cont roller valve to attain the expected temperatures. The temperature of the sample surface is recorded every 5 minutes of both levels by controlling the gas flow to the temperature needed. The condition of the sample is also recorded after the burning process is done. All the physical appearances are captured and are analysed in the results.

Figure 1.1: Thermal properties analyser: (1) TM–30; (2) probe; (3) EFB sample
2.2.3 Termite Procedure

In this research, 50 to 60 termites are prepared to be tested to work on the EFB fibre coated with cement. There are 2 bottles provided, where sample 1 is EFB fibre coated with cement and sample 2 is the EFB fibre itself. Both samples have different weights but they do not affect the results. Each bottle of sample 1 and sample 2 are experimented with 2 types of termites from different species. ‘Subterranean Termites’ (Coptotermes curvignathus), which are bigger than other species found in Malaysia, normally nest and breed in wet basements. The other species is ‘Drywood Termites’ (Cryptotermes cynocephalus) which live in dry areas and consume dry wood tissues. Termites of this species are difficult to detect because they generally live inside dry wood full of mineral. For the first experiment, each bottle contains 50 termites; 15 are soldier Subterranean Termites and the rest are worker termites. The sample bottles and their contents need to be sterilized at 120° C for 2 hours to make sure the bottles are free from bacteria or other living microorganisms (Zaidon et al., 2008). Highly fertile moist soil is put together with the sample since the termites need it. The soil will remain dry for several days due to the drying process at room temperature and this will attract termites to regard the EFB fibre as a food source.

The test bottle and the soil are prepared according to ASTM D3345-74 (ASTM 1998). Before the data can be collected, the weights of both sample fibres are documented to examine weight lost after 4 weeks of observation and after the end of the termites’ life cycle. The temperature needed for the termite is around 26 ± 1°C at room temperature. Every day the temperature is observed to ensure the termites are kept healthy during the length of the experiment. The sample bottles have been placed in a dark area where termites mostly prefer. Within the 4 week timeframe, the EFB’s weights are recorded every 2 days to ascertain the minimum change of each sample’s weight. After the subterranean termites are dead by day 28, the second species, Dry wood termites, is applied to the second experiment. The bottles and the contents are the same as previous procedures. The only exception is that 60 Dry wood termites are released into each bottle with a balanced ratio of 1:1 for termite distribution i.e. soldier and worker 30 – 30. This is observed until the end of the termites’ life cycle for maximum of 28 days.

2.2.4 Mold test procedure

The last test in this research is the mold resistant test. Existence of fungal to product can change the properties of the material. In other way, fungi can cause severe aesthetic changes to products designed to be aesthetically pleasing and also can cause for a health endangerment. The mold experiment in this research for the sample are following ASTM C 1338-08, two sample of EFB fiber been tested, Sample 1 is the sample of EFB fiber mix with cement and chemical binder and sample 2 is EFB fiber without any mixing material. Two bottles are filled with organic sand which can expedite the process growth of fungi with high humidity is 95% and the room temperature is around 26 – 29°C. According to Jerusik (2010), temperature over 30 - 37°C can slow down mold growth and optimal growth was evident between 22 and 29°C. The viability control sample was inspected every 3 days. The sample was periodically checked for growth during incubation period for 28 days. The sample was placed at the area which exposed to the light and not in the dark area, according to Szczepanowska and Lovett (1992) light was a positive influence on the growth of fungi and enhanced with light exposure compared to growth in the dark.
3 Results and Discussions

3.1 Thermal Conductivity Data

In table 1.3, the best result for the thermal conductivity test is sample 2, with the lowest figure of 0.118 W/m.K, which is mostly better than other materials like plasters, papers and etc. Sample 3 with 20mm thickness possesses the lowest density among 3 samples obtained, 0.125 W/m.K which is better than sample 1 which has the highest density and thickness.

Table 1.3: Thermal properties of each sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thermal Conductivity (W/m.k)</th>
<th>Calorific Capacity Cp (J/m³.k)</th>
<th>Thermal Diffusivity (a·m²/s)</th>
<th>Temperature (°C)</th>
<th>Mean Surface area (m²)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>0.149</td>
<td>0.626 E⁺⁶</td>
<td>0.238 E⁻⁶</td>
<td>31</td>
<td>900</td>
<td>80</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.118</td>
<td>0.512 E⁺⁶</td>
<td>0.231 E⁻⁶</td>
<td>31</td>
<td>900</td>
<td>80</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.125</td>
<td>0.259 E⁻⁶</td>
<td>0.482 E⁻⁶</td>
<td>31</td>
<td>180</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1.4: Type of different materials for the Thermal Conductivity value

3.2 Fire Resistance

In this experiment, the samples are tested at different temperatures for 2 hours. The results conclude that EFB fibre mixed with cement is a fire retardant material suitable for use in building/construction. The results of physical surface can be seen in Table.1.4. It shows that after 2 hours of burning at the highest temperature of 1100°C, the samples remain strong especially on the surface not exposed to direct flame. Sample loss from the whole experiment is 40mm, half from the original thickness of 80mm. The efficiency of smoke produced from the material is also reviewed in Table 1.5. The results conclude that there are no black or white smoke being produced during the burning process.
Table 1.5: The sample surface and physical appearance after 2 hours

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 - 600°C)</td>
<td>(0 - 1100°C)</td>
</tr>
</tbody>
</table>

Figure 1.2: Temperature over the time of burning process

Figure 1.2 shows that the temperature is not constant on the samples' surface since heat seems to be easily released into the air and not retained inside the samples. This argument is proven because flame has been supplied continuously to the surface of the samples for the whole duration of experiment since they have low heat capacity.

3.3 Termite attack

The data evaluated based on the original weights of the EFB fibre samples that have been placed together with termites will be compared to the weights of EFB fibre samples after 4 weeks of observation. Resistance to termite attack is calculated based on the percentage of weight loss \[\frac{(W1 - W2)}{W1}\] 100 from the conditioned weight before exposure (W1) and after exposure (W2). The percentage of termite mortality (No/Ni) X
100 in the test bottles is also calculated based on the number of dead termites (No) and the Original number (Ni) [12].

3.3.1 Percentage of Weight loss;
• Experiment 1 with Subterranean Termites
  \[ \frac{(W1 - W2)}{W1} \times 100 \]  
  \[ \frac{(74 - 73)}{74} \times 100 \]  
  1.35% (Percentage of Weight loss after 28 days)
• Experiment 2 with the Drywood Termites
  \[ \frac{(W1 - W2)}{W1} \times 100 \]  
  \[ \frac{(73 - 73)}{73} \times 100 \]  
  0% (No weight loss in experiment 2)

3.3.2 Percentage Termite Mortality
• Experiment 1 with Subterranean Termites
  \( \frac{No}{Ni} \times 100 \)  
  \( \frac{50}{50} \times 100 \)  
  0% (The percentage of mortality after 28 days)
• Experiment 2 with Drywood Termites
  \( \frac{No}{Ni} \times 100 \)  
  \( \frac{60}{60} \times 100 \)  
  0% (The percentage of mortality after 28 days)

![Weight over Day](image)

*Figure 1.3: Subterranean Termites life and sample weight*
Figure 1.4 shows that the weight data is constant for the 28 days of experiment, proving that the termite of both species are not attracted to use EFB fibre mixed with cement as their natural food, and because of this the percentage of the attack results is almost zero and the termite cannot survive on the material for 28 days. The experiment also concludes that Drywood termites survive longer than subterranean termites. Both termites can survive even longer in the sample without binder rather than in the sample with binders.

### 3.4 Mould Resistance test

The mould resistance experiment follows the standard ASTM C 1338-08. Two bottles filled with organic sand can expedite the process of fungi growth with a high humidity of 95% and placed at room temperature around 26 – 29°C. The same samples are used as the termite test samples; one sample is without binders and another one is with the cement binders. The results conclude that the sample without binders is easily affected by fungus in the 10 days of experiment. Meanwhile, the sample with cement binders is also affected by fungus but only during the final week of the experiment i.e. week 4. Fungi growth on the surface of the sample with binders is 0.8% compared to 40 % for fungi growth on the surface of the sample without binders.
4 Conclusion

From the comprehensive experiment results, EFB fibre mixed with cement insulation concludes that this material is insusceptible to fire, termites and also mould attacks. The main results of the thermal conductivity figure show that this material can provide good protection to internal building layers from heat transmission and the efficiency of the waste material can reduce environmental problems.

Acknowledgements

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Abstract: The existing lighting system in Universiti Kuala Lumpur-British Malaysian Institute (UniKL-BMI) is manually controlled and continuously operated. The lack of a control mechanism leads to energy waste and high maintenance cost. Thus, an automated lighting system is proposed in this research to reduce the system's energy consumption. The Integrated Environmental Solutions (IES) software was used to study the lighting intensity of the PC area in the library without the presence of artificial light and establish which area needs light and which area does not. The modelling result was then compared with actual lux measurement, and a correlation coefficient between the modelling and the measurement was observed to be 0.999. Additionally, the actual electricity consumption of an existing 36 W lighting system was found to be 40.7 W due to the impedance of the ballast which produced heat when the lamps were operating continuously. Thus, for the whole lighting system at the PC area comprising of 69 lamps, 324.3 W of energy were wasted on average. Therefore, a light control circuit with an impedance of 83.6 Ω representing the ballast was designed and tested to add greater control of the existing lighting system resulting in estimated energy and cost savings of 2906 kWh/year and RM1061/year, respectively.

Keywords: Lighting intensity, 36W fluorescent lamp, ballast, power loss, controller circuit
1 Introduction
The electrical energy consumed in Malaysia is approximately 22% (Energy Commission, 2015). The major energy users in Malaysian commercial buildings are air conditioners (57%), followed by lighting (19%), lifts and pumps (18%) and other equipment (6%) (Saidur, 2009). Therefore, building automation systems (BAS) are commonly used for reducing a building’s energy consumption, which deals with monitoring and control of building services, such as heating, ventilation and air conditioning (HVAC), lighting and alarms (Bellido-Outerino et al, 2012).

Lighting control system is an intelligent network that communicates between various system inputs and outputs using one or more central computing devices. This system is widely used in commercial, industrial, and residential spaces, for both indoor and outdoor lighting (DiLouie, 2008).

The lighting system controls the artificial lighting level based on presence sensors to match the user’s actual need and help save energy costs. This system also helps to improve user’s comfort and the system’s efficiency (Martirano, 2011).

Librarians at UniKL-BMI library are responsible to control the lights manually. However, the library is underused most of the time due to class activities during the weekdays. This leads to energy waste when the lights are on during unnecessary times. The aim of this research is therefore to develop and test a lighting control system that can provide the right amount of light where and when it is needed.

2 Methodology
2.1 UniKL-BMI Library (PC Area)
Figure 1 shows the Personal Computer (PC) area at the level 8 of UniKL-BMI library. The area is an open space with three windows covered with blinds.

Figure 1: UniKL-BMI library layout with the location of the PC Area

The floor area of the PC area is approximately 136.79 m². Figure 2 shows the existing lighting units based on the actual configuration of the PC area consisting of 23 reflector casings which comprised of 3 fluorescent tubes.
According to European Standard for Energy Efficiency (EN 15232), the current lighting system in UniKL-BMI library is categorized as Class D. Class D describes that the whole system operation in the library is operated manually (Martirano, 2011). On average, the operating hours of the library are from 8.30 am to 7.00 pm continuously during weekdays, and are off during weekends.

2.2 Research Methods

There were three methods used for this study. Firstly, energy model was developed by using simulation from IES and actual measurement by using lux meter. Secondly, the power consumption of 36W fluorescent lamp was measured for 9 hours consecutively by using an energy meter. Finally, an automatic control circuit was developed to control fluorescent lamp operations depending on occupancy at the PC area.

2.2.1 Energy modelling by IES and lux meter

The purpose of this modelling is to observe the lighting intensity of the PC area, without the presence of artificial light. The modelling will be used to determine which area needs light, and which does not. Figure 3 shows the actual dimension of the area.
A simulation was carried out to predict the lighting intensity of the area. Grid lines were drawn between the tables to mark the measuring points of the light intensity. After simulation, the actual illuminance was measured at the centre of each table. The measurement must be taken from the same height. Different ceiling height gives different light distribution to its surface (Meyers-Levy et al., 2007), therefore leading to inconsistent lux reading. This measured lux values were compared with the values from IES. Table 1 shows the related information to the IES simulation.

Table 1: Related information to the IES simulation

<table>
<thead>
<tr>
<th>Related information to the IES simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Sky condition</td>
</tr>
<tr>
<td>Height of tables</td>
</tr>
<tr>
<td>Ceiling height</td>
</tr>
<tr>
<td>Height from window to wall</td>
</tr>
<tr>
<td>Height of external wall</td>
</tr>
<tr>
<td>Windows condition</td>
</tr>
<tr>
<td>Building orientation</td>
</tr>
</tbody>
</table>

2.2.2 Power consumption of the existing lamp

The lamps used at the PC area are Philips fluorescent 36 W. The lamp system comprises of ballast, which limits the amount of current going through the lamp tube by providing a positive resistance that limits the current. However, the ballast has an internal resistance that contributes to the power loss of the lamp (Csele, 2004).

The electricity consumption of the existing lamp was determined by using an energy meter. The electricity consumption in Watt (W) and kilowatt per hour (kWh) were recorded from 8 a.m. to 5 p.m. at an interval of one hour. The recorded data were verified with a simple analytical method based on equation (1).

\[ \text{Power} = I \cdot V \cdot \cos \Theta \]  
(1)

The purpose of this method is to find the power loss of the lamp when the electricity was overly consumed during its operation. In order to determine the power loss, the power rating of the lamp was subtracted from the overall power consumption. The results obtained from this experiment were used to determine the internal impedance from the ballast of the lighting system, for further clarification purpose. The impedance can be determined by using equation (2).

\[ V = I \cdot Z \]  
(2)

2.2.3 The development of automatic control circuit

Figure 4 illustrates an automatic control circuit which was developed during this research, by using Multisim software. Figure 5 shows the actual circuit which was developed and tested.
The circuit was developed by using an RE 200B Pyroelectric Infrared Sensor (PIR), which detects any movement at the area. The circuit controls the operation of the lamps by turning it on when there is occupancy, and off when there is no occupancy. Multisim was used to simulate the operation of the circuit and also to compute the desired output voltage. The input of the circuit was 12.38 V, while the expected output was 11.69 V. The output was used by a relay to control the switching of the fluorescent lamp.
3 Results & Discussion
For this section, the results are summarised and discussed into three segments. The segments include the modelling results for lighting intensity at the PC area; the energy consumption for 36W fluorescent lamp which includes its power loss and internal impedance calculation; and lastly, the output of the automatic control circuit. In addition, the energy saving cost and the payback period for the lighting system are presented.

3.1 Modelling results at the PC area using IES and lux meter
Figure 6 shows the simulation result of lighting intensity at the PC area by using IES software. The colour contour indicated the lux value (brightness) of the area.

![Figure 6: Lighting intensity simulation result in IES](image)

The modelling was conducted when the artificial lights were turned off, both by simulation and lux measurement. It is important to observe how much daylight can enter the area, to determine the lighting zones. These lighting zones can determine which luminaires need constant light, and which luminaires does not. In order to verify the predicted values, the actual illuminance was determined by using a lux meter. Table 2 shows the comparison of the predicted and the measured lux values.

<table>
<thead>
<tr>
<th>Area</th>
<th>IES Simulation (lux)</th>
<th>Lux meter measurement (lux)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>55</td>
<td>56</td>
<td>-1.8</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>46</td>
<td>-2.2</td>
</tr>
<tr>
<td>C</td>
<td>35</td>
<td>33</td>
<td>5.7</td>
</tr>
<tr>
<td>D</td>
<td>25</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>11</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>12</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>9</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>W1</td>
<td>&gt;100</td>
<td>19930</td>
<td>N/D</td>
</tr>
<tr>
<td>W2</td>
<td>&gt;100</td>
<td>8040</td>
<td>N/D</td>
</tr>
<tr>
<td>W3</td>
<td>&gt;100</td>
<td>7950</td>
<td>N/D</td>
</tr>
</tbody>
</table>
Predicted and measured lux values for tables A to H vary from -2.2% to 5.7%. The observed consistency may be due to the setting of the simulation software which considers the actual condition of the measurement, which is the reflective and light absorbing surfaces of the area, the stable sky condition, and the height of the tables which are consistent.

The difference in simulated and measured illuminance could not be computed for windows because the lux range is limited to 100 lux in IES software, which explains why the measurements at the windows can be up to almost 20,000 lux.

According to the Malaysian Standard 1525, the optimum illuminance of an office is 300 lux. Since the blinded windows only allow low daylight penetration into the PC area, the area requires artificial lights to match its optimum illuminance.

### 3.2 Energy consumption for 36 W fluorescent lamps

Figure 7 illustrates the comparison between the fluorescent lamp’s power rating and its measured power consumption.

![Figure 7: Power consumption for fluorescent lamp (W) for 9 hours](image)

Based on specification, the lamp should consume 36 W of power. However, the ballast system caused the electricity to be overly consumed up to 42.4 W during its operation. In average, 4.7 W of power was overly consumed, which is 11.4% of the energy consumption. From the power loss obtained, the value of impedance of the ballast was calculated from equation (2) and (3):

$$ R = |Z| \cdot \cos \Theta $$

(3)

From equation (3), the impedance value of the ballast is 83.6 Ω, which was the contributor for the power loss during the lamp’s operation. Higher impedance leads to higher voltage, and higher power consumption. Figure 8 compares the results of measured total electrical energy consumed by the lighting system with the estimated electricity consumed by the 36 W fluorescent lamps.
Over time, the energy gap keeps increasing, illustrating the energy loss due to the ballast. The average energy loss was found to be 0.03 kWh, which is 18.7% of the energy consumption. This energy waste resulted in higher electrical billing.

3.3 Automatic control circuit output

The output of the control circuit simulated to be 11.7 V, whereas the actually measured voltage was found to be 10.5 V. This value was 9.9% lower than the predicted voltage possibly due to the tolerance value of the components in the actual circuit by ± 5%. Furthermore, the voltage regulator in the actual circuit reduces the output voltage to 8 V. These conditions are different from the controlled environment of the simulation. However, the relay was still able to deliver output for lamp switching. Figure 9 shows the circuit diagram for the automated lighting system.

![Circuit diagram for automated lighting system](image)

The control circuit are installed in between the power supply and the 36 W fluorescent lamps in one panel. This circuit will control the operation of the lamps depending on the presence sensor.
3.4 Energy Saving Cost

After the power loss of the fluorescent lamp was measured and a control circuit was developed, the amount of energy that can be saved when the lights are not used throughout the semester in one year was estimated. For a building like UniKL-BMI, the tariff used is C1 (Medium Voltage General Commercial) tariff. The rate is RM 0.365 per kWh.

\[
\text{Energy saved in a year} = \text{learning weeks} \times \text{days} \times \text{hours of unused energy (h)} \times \text{lamp energy (kW)} \times \text{lamp unit} \\
= 52 \times 5 \times 4.5 \times 0.036 \times 69 \\
= 2906.28 \text{ kWh/year}
\]

\[
\text{Cost saved in a year} = \text{energy saved/year} \times \text{TNB tariff per kWh} \\
= 2906.28 \text{ kWh/year} \times \text{RM 0.365} \\
= \text{RM 1060.80/year}
\]

RM 1060.80 can be saved in a year. The estimation was based on UniKL BMI library’s average operational hours during weekdays.

3.5 Payback period

For installation cost, it covers the cost for developing the automatic control circuit. One circuit will be placed at each lamp panel at the PC area. The area has 23 lamp panels, which comprise three fluorescent lamp tubes that are in parallel connection.

\[
\text{Payback Period} = \frac{\text{Installation cost} \times \text{lamp panel unit}}{\text{Savings per year}} \\
= \frac{\text{RM 110} \times 23}{\text{RM 1060.80}} \\
= 2.4 \text{ years}
\]

The estimated payback period of 2 years suggests that the installation of the automatic control circuit is an economically viable investment. While the payback period was calculated without taking interest rate into consideration, it should be considered that the electricity costs are likely to increase which will offset increase in payback period due to interest rate. When lighting system is efficient, less maintenance is needed and the fluorescent lamps can last longer resulting in further savings. There are possibilities for one circuit to be installed to two lamp panels instead of one panel to save more money.

4 Conclusion

The predicted and measured lux values varied between -2.2% to 5.7%. The observed consistency may be due to the setting of the simulation software which considers the actual condition of the measurement, which is the reflective and light absorbing surfaces of the area, the stable sky condition, and the height of the tables which are consistent. However, due to low daylight penetration into the PC area, the area requires artificial lights to match its optimum illuminance.

The 36W fluorescent lamp was found to waste 4.7 W due to the ballast. In order to reduce the power loss of the fluorescent lamp it is proposed to install a stabiliser circuit to replace the ballast.
The designed automatic control circuit was able to successfully operate the lamp switching, despite a 9.9% lower voltage than predicted. Electricity and energy savings were estimated to be 2906 kWh/year and RM1061/year, respectively.

Acknowledgements
I would like to thank Siti Nur Aisyah Abdullah for her expertise in electronic circuit, and UniKL BMI Research & Innovation team members for their expertise and endless moral support during this research.

References


ENERGY BALANCE OF AN ENERGY EFFICIENT HOUSE IN MALAYSIA

Nur Hafifah Ismail¹, Stephanie Bacon², Gregers Reimann³ & Robert Thomas Bachmann¹

¹ Malaysian Institute of Chemical and Bioengineering Technology, Universiti Kuala Lumpur, 78000 Alor Gajah, Malaysia, and University of Applied Sciences Rosenheim, 83024 Rosenheim, Germany, hafifah.ismail91@gmail.com and bachmann@unikl.edu.my
² CoolTek, Malaysia, cooltek.my@gmail.com
³ IEN Consultant, Malaysia, gregers@ien.com.my

Abstract: The growing population in Malaysia is increasing the demand for housing, which is bound to increase building energy consumption and hence contributes to global warming and faster depletion of our resources. The amount of energy consumed by buildings may be influenced by climate parameters, the building envelope, energy systems, and behaviour or activities of occupants, which have to be considered in order to identify energy efficiency potentials and saving opportunities. There is growing individual and commercial effort to develop energy efficient buildings such as the Cooltek house located in Melaka, Malaysia, which has won the First Runner Up in the ASEAN Energy Awards 2009. The main objectives of this study are to carry out an energy audit of the CoolTek house and conduct computer simulations to test performance and effectiveness of the passive and active energy saving features. The energy consumption of the electrical appliances in the CoolTek house was measured using portable electricity consumption meters. IES (virtual environment) simulation software was used to predict the impact of different energy efficient features of the house i.e. roof insulation, floor insulation, and double-glazed units on the overall energy consumption of the CoolTek house. From the energy audit it was found that the air-conditioning unit was the main electricity consumer followed by a refrigerator and lighting. The average energy consumption per area was found to be 1.38 kWh / (m².month). The conversion efficiency calculated was 38% which equivalent to 3.6 kWh/ (m².month) primary energy demand which is below the threshold of primary energy consumption for energy efficient buildings of 10 kWh / (m².month). The combined conduction gains from the roof, external walls and glazing accounts for 67% of the overall heat gains. The proper usage of internal insulations for roof inclusively, better performing windows and shading were identified to be the key parameters that cut down energy consumption.

Keywords: energy consumption, energy efficient, simulation, measurements
1 Introduction

Agreeing to European Parliament and Council 2010, buildings account for a surprisingly high 40% of overall energy consumption and 36% of carbon dioxide emissions in the European Union (EU) (Ahmad, 2014). According to Malaysia’s Energy Statistics Handbook 2015, total electricity consumption in 2013 was 123,076 GWh of which commercial and residential buildings consumed 48% (Tenaga, 2012). A research conducted by Centre for Environment Technology and Development in Malaysia (CETDEM) indicated that air conditioners and refrigerators takes up nearly 70% of the average building electricity usage. Air conditioner was found to be the largest consumer of electricity in Malaysian residential buildings (Hassan, 2014). By year 2020, the population is expected to be 32.4 million people (Malaysia, 2015). This implies that the demand for housing and energy consumption will increase too due to the usage of modern home appliances.

In addition, Malaysia experienced hot and humid climate throughout the year. Cooling system are increasingly used to remove heat from a building to maintain a certain temperature for occupant’s comfort. Heat in a building is generated from solar radiation, influx and heat gain from people and electrical equipment. The amount of heat generated by each element may vary different between buildings.

In order to save energy, it is recommended to first test and introduces passive features before an attempting to optimise active system in buildings (Sartori, 2007). Passive technologies include increased insulation, better performing windows, reduction of air infiltration losses and shading devices. Active technologies include principal mechanical (HVAC), lighting and occupancy controls as well as photovoltaic panels. Energy efficiency will help to reduce the burden of energy costs for the consumers but at the same time ensure that the energy quality and quantity derived from the energy used are maintained.

To be comfortable, the owner together with the designer and architect had come out with passive and active cooling strategies in the house. The passive cooling strategies including orientation, ventilation, shading and insulation were determined by climate, so the climate zone in Melaka, Malaysia was first identified. Active cooling in CoolTek house is provided by an air-conditioning system located in the bedroom and office room which include air infiltration and humidity control.

In 2008, the first energy audit was conducted and the electricity consumed in 2008 was a total of 8,636 kWh, giving an energy index of just 37.2 kWh / m².a due to the energy efficient electrical appliances installed in the house and the passive cooling strategies applied (KTAK, 2009). The urgency to conduct another energy audit as well as the energy simulation due to the fact that some electrical appliances were replaced with brand new and more efficient appliances such as air-conditioning system, refrigerator, desktop and etc. and the house is occupied by one person now.

The main purpose of this research is to carry out an energy audit on an energy efficient house located in Melaka, namely CoolTek house and conduct computer simulations to establish its performance and effectiveness of the passive and active energy saving features.
2 Methodology

2.1 General Description

The CoolTek house, a highly efficient residential building, was chosen for this study. The house located in Tiara Melaka Golf and Country Club (Latitude: N 2.279731, Longitude: E102.316771) whose construction finished in 2004. The single-storey house has a gross floor area of 239.62 m\(^2\) and it is inhabited by one person. The house was built and installed with energy efficient features in order to make use of the relatively predictable Malaysian weather for thermal comfort purpose. Figure 1 shows the ground floor plan of the CoolTek house drawn in IES\(^\circ\)VE.

![Figure 34: Ground floor plan of the Cooltek house built in IES\(^\circ\)VE based on 2D CAD drawing.](image)

The breakdown of the floor area of CoolTek house is shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Room Name</th>
<th>Floor Area (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Master bedroom</td>
<td>21.95</td>
</tr>
<tr>
<td>2</td>
<td>Guest bedroom</td>
<td>12.60</td>
</tr>
<tr>
<td>3</td>
<td>Ensuite</td>
<td>8.16</td>
</tr>
<tr>
<td>4</td>
<td>Family bathroom</td>
<td>6.09</td>
</tr>
<tr>
<td>5</td>
<td>Office room</td>
<td>19.20</td>
</tr>
<tr>
<td>6</td>
<td>Living room</td>
<td>77.50</td>
</tr>
<tr>
<td>7</td>
<td>Kitchen</td>
<td>11.57</td>
</tr>
<tr>
<td>8</td>
<td>Work area</td>
<td>10.24</td>
</tr>
<tr>
<td>9</td>
<td>Store</td>
<td>9.28</td>
</tr>
<tr>
<td>10</td>
<td>Garage</td>
<td>40.87</td>
</tr>
</tbody>
</table>

2.2 Topography and Climate data

The CoolTek concept was developed by the owners who expected the house to provide them with a comfortable range of indoor air climate of 18\(^\circ\)C to 24\(^\circ\)C at a relative humidity (RH) range of 40% to 70%. In order to do so, the house was orientated with the shortest
length of walls facing East and West to restrict heat gain from morning and afternoon sun respectively. The East and West walls are also shaded away from the sun by vegetation. The building site is located in the open countryside with a low buildings density.

The daily temperature and relative humidity was monitored using a “Davis” weather station mounted on the roof. The average outdoor temperature and relative humidity during the experimental period are shown in Figure 2.

The outdoor temperature is ranged between 24°C to 33°C, reaching maximum values in the afternoon, while the relative humidity varied between 68% and 82%.

Figure 35: Outdoor temperature and relative humidity of CoolTek house from August – October 2016

Figure 36: Temperature and relative humidity inside office room of CoolTek house (August 2016-October 2016).
The measurements show that the inside office room, air temperature varied from 27°C to 28°C and relative humidity from 58% to 65%.

2.3 Building Construction and Materials

All fenestrations were set deep into the external walls and are sheltered by deep overhangs that stretch around the house. The structural system of the house was made up of load bearing walls and built with 250 mm thick autoclaved lightweight concrete (AAC) blocks and painted white to lessen heat transmissions. AAC blocks are light and can be cut effortlessly according to wall design, thus reducing construction material wastage and costs. The reinforced concrete floor was insulated with rigid 50 mm thick polyurethane insulation boards and finished with laminated timber board on top. The imported windows from United Kingdom are with exceptionally low thermal transmittance, double panes of glass with a low emissive coating on one side of one pane and the gap between the panes filled with argon gas to stop heat radiating passing through.

The ground cooled system ventilates the house with fresh air since the house does not have any openable windows and all doors to the outside have double-seals to ensure air tightness of the building envelope (Reimann, 2007). Warm air was then expelled through a solar chimney located above the refrigerator in the kitchen (Figure 1).

2.4 Description of Electrical Systems

In this section, a description of all major electrical systems such as lighting, cooling, and auxiliary devices existing in the single-storey house, which contributed to the energy usage are presented.

2.4.1 Lighting systems

CoolTek house is equipped with 25 Watt ALETKO energy saving lamps in the living room, office, bedroom and kitchen. Due to sufficient daylight harvesting, the lights are switched on only night.

2.4.2 Cooling systems

Two energy efficient split air-conditioners (Panasonic, CS/CU-S13PKH) with R410a hydrofluorocarbon (HFC) refrigerant (Table 2) were fitted to assist with the reduction of indoor air temperature and relative humidity, RH to comfort range.

<table>
<thead>
<tr>
<th>No</th>
<th>Room Name</th>
<th>Type of cooling unit</th>
<th>Number of cooling units</th>
<th>Cooling Capacity (kW)</th>
<th>COP</th>
<th>Operation hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Master Bedroom</td>
<td>Air-conditioning</td>
<td>1</td>
<td>3.66</td>
<td>2.61</td>
<td>10:00-23:00</td>
</tr>
<tr>
<td>2</td>
<td>Office room</td>
<td>Air-conditioning</td>
<td>1</td>
<td>3.66</td>
<td>2.61</td>
<td>23:00-10:00</td>
</tr>
</tbody>
</table>

2.4.3 Auxiliary equipment

The auxiliary equipment existing within selected room of the house is presented in Table 3. This equipment is taken into consideration when internal gains are counted during energy simulations.
Table 18: Auxiliary equipment per room in the CoolTek House

<table>
<thead>
<tr>
<th>No</th>
<th>Room Name</th>
<th>Appliances</th>
<th>Nominal Power (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Master bedroom</td>
<td>Electric Iron</td>
<td>1049</td>
</tr>
<tr>
<td>2</td>
<td>Office room</td>
<td>Phone Charger</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PC</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>Living room</td>
<td>TV</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum Cleaner</td>
<td>1552</td>
</tr>
<tr>
<td>4</td>
<td>Kitchen</td>
<td>Washing Machine</td>
<td>2800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kettle</td>
<td>2245</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dishwasher</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Microwave</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Refrigerator</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toaster</td>
<td>863</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>12509</strong></td>
</tr>
</tbody>
</table>

All electrical appliances in the house are energy efficient certified and switched off when not in use except for the refrigerator which is conveniently placed under thermal chimney to instantly expel all generated heat (Figure 1).

2.5 Measurements

The actual electricity consumption of the house was monitored from 14th August until 21st October 2016. The energy consumption of the electrical appliances in the CoolTek house was measured using UT230B Series Power Metering Socket. This power metering was equipped with high precision current sensor to give a real-time monitoring to AC power supply unit. The energy consumption of air condition units was obtained by deduction of the energy consumption of all other electrical appliances during the same monitoring period from the total energy consumption.

2.6 Modelling with IES simulations

The measured data were compared with simulation data, obtained using IES <Virtual Environment> version 2015.2.1.0. This software meets the requirement of ASHRAE Standard 140 and CIBSE AM11 for a building dynamic energy simulation tool. A simulation of the energy performance of the CoolTek house was carried out using ModelIT. This software provides a range of environmental performance data such as; energy consumption, internal comfort data and HVAC component details. A model of the CoolTek house was developed and the entire house treated as one zone for energy calculation. SunCast was used to perform basic solar studies and ApacheSim to perform dynamic thermal simulations according to mathematical modelling of the heat transfer mechanisms occurring in and around the building.

2.6.1 Climate Data

Weather data for the CoolTek house are required for a realistic energy performance analysis. The IES weather file from the ASHRAE International weather for Energy Calculations (IWEC) data for Kuala Lumpur was used for the simulation of the energy performance of the CoolTek house. The IES weather file from the ASHRAE International weather for Energy Calculations (IWEC) data for Kuala Lumpur was used for the simulation of the energy performance of the CoolTek house (International Weather for Energy Calculations, 2001).
2.6.2 Setting Lighting, Cooling and Equipment Profiles
The air conditioning system in CoolTek house is operational 24 hours for the occupant’s thermal comfort requirements. One unit located in the office room is operating from 10 am until 11 pm while another located in the bedroom was switched on from 11 pm until 10 am. The temperature set point of the cooling system was always 24 °C.

The lighting system was operated from 7 pm to 11 pm. According to the owner, only five bulbs with 25 W each were installed with one on/off switch located in the living room, which was switched on to provide a good lighting environment to the occupant during the night time.

2.6.3 Thermal and construction data for Building Template Manager (BTM)
Lighting, cooling and equipment profile were created in Building Template Manager (BTM). A construction template for external and internal wall, internal floor, roof and glazing was created by taking into consideration the construction material thermal properties (Table 4).

<table>
<thead>
<tr>
<th>Table 19: Thermal properties of building components from CoolTek house</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>House components</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>External Walls</td>
</tr>
<tr>
<td>Roof</td>
</tr>
<tr>
<td>Floor</td>
</tr>
<tr>
<td>Windows</td>
</tr>
<tr>
<td>External door</td>
</tr>
</tbody>
</table>

3 Results and Discussions

3.1 Electricity Consumption Monitoring
The energy demand of the CoolTek house was monitored using portable energy meter and recorded. As can be seen from Figure 4, air-conditioning system was the main electricity consumer; 217 kWh and 278 kWh for September and October respectively, followed by fridge (44.1 kWh) and lighting (10.5 kWh). The average energy consumption per area was found to be 1.38 kWh / (m².month). The conversion efficiency calculated was 38% which equivalent to 3.6 kWh/(m².month) primary energy demand which is below the threshold of primary energy consumption for energy efficient buildings of 10 kWh / (m².month) (Zangheri, 2009).
3.2 Energy Simulation

The simulated energy demands for the CoolTek house in September and October is given in Figure 5. The house area used for this calculation was 179.2 m², which covered the area of the air-conditioned zone and the kitchen (Figure 1). From the graph, it can be concluded that the most energy consuming application is cooling accounting for 1.40 kWh/m².month followed by auxiliary equipment energy (0.40 kWh / m².month) and lighting (0.10 kWh / m².month).
The total predicted electricity demand for the CoolTek house was 1.94 kWh / (m².month), equivalent to 5.1 kWh / (m².month) which is lower than the revised Passivhaus Standard for buildings formulated by Passive-On Consortium for the application of the Passivhaus Standard in Warm European Climate, (10 kWh / m².month) (Zangheri, 2009). The fact that can be appointed to the proper care devoted in the initial phase of design and construction of the CoolTek house. Moreover, the avoidance of thermal bridges in every elements connection and the increased insulation thickness in roof and ground elements are the major advantages that act as barriers towards heat transfer into the house. Moreover, most of the old buildings in Malaysia have singled glazed windows with relatively high U-values and loses occurring through the metal frame. In the case of CoolTek house, the window is double-glazed with uPVC frame, resulting in low U-value (Table 4).

The simulated heat balance of the CoolTek house during cooling period is shown in Figure 6. The combined conduction gains from roof, external walls and glazing account for 67% of the overall heat gains. The heat gain from the roof has the highest influence on the cooling requirement due to the large surface area, the year-round exposure to the sun and the fact that CoolTek is a single storey house. The simulated heat gain from one occupant was found to be 0.6 kWh / (m².month) and 0.7 kWh / (m².month) for September and October respectively which agrees with values reported in literature (Handbook, 2001). The infiltration rate from the ground ventilation was 1.67 ach (Amernudin, 2016) resulted in heat gains of 0.5 kWh / m².month.

The finding agree well with (Dziugaite-Tumeniene, 2012), who reported that the main critical factors affecting the characteristics of the building and energy system are (i) heat transfer coefficients of the walls, windows, roof and floor, (ii) solar heat gain coefficient.
(SHGC) of the windows, (iii) orientation of the house, (iv) efficiency of the cooling units and (v) set-point temperature for space cooling.

Different design elements of the CoolTek house were simulated to quantify the effect on the annual energy consumption. By removing floor or roof insulation, the electric consumption increased by 37% and 71%, respectively (Figure 7). Changing the double glazed unit to single pane windows only had minor impact on the annual electric consumption due to the north-south position of the windows and the 1.06 m roof overhang providing additional shading. Meanwhile, reducing the roof overhang to zero has increased the annual electricity by 8%.

![Figure 40: Different variations of CoolTek house on the annual electric consumption.](image)

4 Conclusions

The measured average monthly cooling demand was found to be 1.38 kWh/m².month slightly lower compared to the simulated cooling demand, 1.40 kWh/m².month. Therefore, during the design stage, the IES® VE simulation software should be used carefully, as too optimistic values could be obtained. The simulated total energy demand for the CoolTek house is 1.94 kWh/m².month resulted to 70 kWh/m²a (assumed primary energy equals to three times electric energy), lower than the Passivhaus Standard for buildings developed by Passivhaus Institut, Germany, in which the primary energy demand for all energy services does not exceed 120 kWh/m²a. The cooling demand for CoolTek house consumed almost 73% of total electricity consumption while auxiliary equipment and lighting consumed 21% and 6% of total electricity consumption respectively.

The simulations showed that the conduction gain from building envelopes accounts for the highest heat gain. Simulation of different building envelope designs have demonstrated that, by removing the floor and roof insulation the annual electric consumption raises by 37% and 71%, respectively. Therefore, insulated roof and floor are suggested to be the most important energy efficiency measures of the CoolTek house. Moreover, CoolTek house has the best design for shading the external wall by extending the roof. Meanwhile, the internal heat gains from persons did not affect the heat gain since only one person occupied the house. However, the simulated heat gains into the house was seems to be
unbalanced (5.5 kWh / m².month) with the cooling demands (1.4 kWh / m².month). A very efficient air-conditioning system contributed a tremendous impact on the electric consumption.

Acknowledgement
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References


[Accessed 10 December 2016].


WORKABILITY OF GROUND COOLING SYSTEM WITH FAN AT COOLTEK HOUSE

Khairol Bin Kamaruddin¹,²,³, Stephanie Bacon⁴, Gregers Reimann⁵ & Robert Thomas Bachmann¹

¹ Malaysian Institute of Chemical and Bioengineering Technology, Universiti Kuala Lumpur, Malaysia, bachmann@unikl.edu.my
² University of Applied Sciences Rosenheim, 83024 Rosenheim, Germany
³ KKTM Sri Gading, Malaysia, khairol@kktmsrigading.edu.my
⁴ CoolTek, Malaysia, cooltek.my@gmail.com
⁵ IEN Consultant, Malaysia, gregers@ien.com.my

Abstract: The CoolTek house in tropical Malaysia is a single-storey domestic building that was designed to be air-tight with ground cooling system and solar chimney providing fresh pre-cooled air to the interior of the building. Previous tests revealed that the solar chimney alone was insufficient to draw fresh air through the sub-soil concrete chambers, and a mechanical ventilation system was proposed and installed. However, the tree that shaded the air intake died thus exposing it to direct sun radiation which in turn may affect the performance of the system. In order to confirm the effect of shading, measurements of temperature, absolute humidity and CO₂ were taken inside the ground cooling air duct, indoor and outdoor CoolTek house during three (3) modes of operation and compared with previous findings. In the fully passive mode the ventilation was driven only by the thermal pull of the solar chimney when air-con and auxiliary fan were off. During passive mode, the ventilation was driven only by the thermal pull of the solar chimney during 24 hours air-condition, while in hybrid mode the auxiliary fan assisted the solar chimney in ventilating the building. The results confirmed that the solar chimney alone is insufficient while the absence of shading increased the temperature of the air at ground cooling intake by 2 ± 0.2 °C. However, CoolTek’s ground cooling systems still delivered an almost constant air temperature of 28°C all day at a 40 % lower cooling load in hybrid mode with saving about 418 kWh/year electricity consumption – or RM137.89 in local currency compared to passive mode. The performance of the ground cooling system could be enhanced by shading the air intake area with either plantation or construct lightweight structure and recirculate the indoor air.

Keywords: Ground cooling system, air-tight, modes of operation, solar chimney, sub-soil concrete chamber.
1 Introduction

Residential building occupants in Malaysia often solve thermal discomfort with air-conditioning, contributing to more than 50% of the building total energy consumption (Chan 2004). Based on the Building Energy Efficient Technical Guideline for Passive Design (BSEEP), a good house design ensures adequate air-tightness of the building envelope. However, some passive house designs experience difficulties with ventilating fresh air (Building Sector Energy Energy Efficiency Project 2013), which results in a high content of carbon dioxide ($CO_2$) causing tiredness, lack of concentration and headache (Lu et al. 2010). One of the solutions proposed to overcome this problem was the use of a ground cooling system to provide fresh precooled air (Katili et al., 2015).

In 2004, a single storey residential building (CoolTek) was constructed as a simple, easily maintainable home to be five times more efficient than a typical Malaysian house even with air conditioning operated all day (Boswell & Bacon, 2005). The CoolTek house with 200 m$^2$ floor area is air-conditioned 24 hours and just consumes 8 kWh/d for air-conditioning system. It fulfils four energy efficient building design features of orientation, protection, insulation and ventilation. The CoolTek house has a flat roof (15˚ pitch) with low ceiling height of 2.4 m and airtight double-glazed doors and windows. The air intake pipe for groundcooling is connected to a sub-soil chamber of 50 mm thick and 1000 mm in diameter concrete culvert, containing 5 concrete filled ceramic pipes standing on a concrete plinth of 300 mm depth with heavy concrete, surface insulated lid. Stale air exits the house through a red brick 4.55 m high chimney aimed to function as a thermal chimney (Figure 1). The overall design strategy of the CoolTek house thus makes it possible to minimise the use of air conditioning (Reimann et al., 2007).

However, Reimann et al. (2007) noticed that the ground cooling system of the CoolTek house was not working as expected, as cooled air from the house appeared to flow out through the ground cooled air duct pipe during day time. Therefore, a 35 W auxiliary fan was installed between the living room and the solar chimney to assist the solar chimney pulling fresh air from ground cooled ducts during daytime. The air temperature delivered by the ground cooling system in the CoolTek was almost constant at 27.2°C throughout the day and night while the maximum outdoor air temperature was 32°C (Reimann et al. 2007) equivalent to a maximum of 5°C reduction. However, the tree that used to shade the air intake opening (Figure 1) died thus directly exposing it to the sun which in turn may affect the performance of the ground cooling system.

Thus, the main aim of this study was to confirm the effect of mechanical ventilation on the operation of the solar chimney and evaluate the effect of shading on ground cooling system.

Figure 1: The ground cooling system of the CoolTek house
2 Materials and Methods

The performance of the system was monitored at 15 min intervals using dataloggers measuring temperature, relative humidity and \( \text{CO}_2 \) levels (Table 1); absolute humidity was calculated using the VAISULA/Humidity Calculator 5.0 (Oyj, 2014).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurements</th>
<th>Accuracy</th>
<th>Logging Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professional Temperature</td>
<td>a) Temperature</td>
<td>± 1°C</td>
<td>15 min</td>
</tr>
<tr>
<td>Relative Humidity Data Logger</td>
<td>b) Relative humidity</td>
<td>± 3%</td>
<td></td>
</tr>
<tr>
<td>CO2 Logger</td>
<td>a) Temperature</td>
<td>± 50 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b) Relative humidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) ( \text{CO}_2 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The dataloggers were placed at three different locations as illustrated in Figure 2. During period A, B, C, E and F, the CoolTek house was air-conditioned 24 hours a day (set point 24°C), except for period D during which it was operated in fully passive mode.

Enthalpy was determined by finding the intersection of the temperature and relative humidity on the psychrometric chart. The enthalpy scale is located above the saturation, upper boundary of the chart. Statistical analysis was carried out using statistical function in Microsoft's Excel software.

3 Result and Discussion

The electricity consumption of the CoolTek building is summarised in Table 2 and was found to vary between 1.5 kWh/d (fully passive) 13.6 kWh/d (passive mode), while outdoor-indoor temperature differences were 1.1°C (fully passive) and 2.6°C (hybrid mode).
When the CoolTek house was air-conditioned and the fan operated for 24-hours (hybrid mode), the energy consumption decreased by 8.8 % to 12.4 kWh/day.

The average 24 hr outdoor temperature profile between the monitoring periods (Figure 3) was found to differ slightly but was of no statistical significance (p=0.005) thus confirming reproducible environmental conditions throughout the experimental period.

<table>
<thead>
<tr>
<th>Table 2: Schedule of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td><strong>A: Outdoors</strong></td>
</tr>
<tr>
<td>(On the bedroom terrace inside a radiation shield)</td>
</tr>
<tr>
<td><strong>B: Inside the house (bedroom)</strong></td>
</tr>
<tr>
<td>(1.2m above the floor)</td>
</tr>
<tr>
<td><strong>C: Inside the house (computer room)</strong></td>
</tr>
<tr>
<td>(1.2m above the floor)</td>
</tr>
<tr>
<td><strong>D: Inside the ground cooled air duct</strong></td>
</tr>
<tr>
<td>(0.5 m below the floor)</td>
</tr>
<tr>
<td><strong>MODE: FULLY PASSIVE</strong></td>
</tr>
<tr>
<td><strong>E: Inside the ground cooled air duct</strong></td>
</tr>
<tr>
<td>(0.5 m below the floor)</td>
</tr>
<tr>
<td><strong>MODE: PASSIVE</strong></td>
</tr>
<tr>
<td><strong>F: Inside the ground cooled air duct</strong></td>
</tr>
<tr>
<td>(0.5 m below the floor)</td>
</tr>
<tr>
<td><strong>MODE: HYBRID</strong></td>
</tr>
</tbody>
</table>
The profiles of average daily temperature were analysed to identify the hour of the day suitable to draw air through the ground cooled air duct in order to pre-cool inlet air into the house (Figure 4).

Figure 4 shows that the indoor temperature was cooler than outdoor temperature especially during day time due to use of 24 hrs air-conditioning. The maximum average outdoor temperature of about 34°C was reached between 3 and 4 pm. However, outdoor temperatures increased by about 4°C compared to values reported by Reimann et al. (2007) for the same house, while the average ground cooled air temperature also increased by about 2°C, probably due to its direct exposure to the sun in the absence of a tree that previously provided shading. In addition, the increase in ground-cooled air
temperature may also be affected by a lower internal air-con set-point if air-conditioned indoor air escapes through the ground-cooled air duct.

Results of ground cooled air ducts temperature in fully passive mode showed that its profile followed the outdoor temperature variation. Reimann et al. (2007) reported that in principle, if there was a steady flow of air through the ground cooled air duct to the indoor environment, one would expect the temperatures to be stable or to reflect the outdoor temperature profiles. Therefore, the system was still performing during fully passive mode. During passive mode, the opposite appeared to be the case indicating reversed air flow in the ground cooled air ducting during the day time. Lastly in hybrid operation mode, the ground cooled air ducts temperature profile was stable at around 28°C, which showed that the ground system effectively can cool incoming outdoor air. This is supposed to happen for the system in order to have good performance for supply cooled fresh air.

3.1 Carbon Dioxide (CO$_2$) Measurements

Figure 5 shows that the CO$_2$ level in the bedroom and computer room follow the same pattern ranging between 600 ppm to 700ppm. The CO$_2$ reading also show that the indoor space was adequately ventilated with readings well within the recommended range of 350 to 1,000 ppm (ASHRAE62.1 2004). The profile of CO$_2$ level for passive mode showed that the ground cooled air duct had the highest CO$_2$ level at day time, as it was connected directly to indoor air. The difference in CO$_2$ level was particularly high at night, where the indoor CO$_2$ levels were about 200 ppm greater than in the ground cooled air duct. The results agrees with finding by Reimann et al. (2007) who observed that the CO$_2$ level of the ground cooled air duct increased by 100 ppm compared to night time levels indicating that the air flow in the pipe has reversed during day time (Reimann et al. 2007). This also suggests that the installed diffuser at the top of ground air duct inlet did not function effectively in passive mode operation.

![Figure 5: Average CO$_2$ measurements (period A – F)](image-url)
During fully passive mode, the profile of CO$_2$ level reflected the outdoor CO$_2$ profile; higher at night time and lowest at day time. At this period, the indoor condition was equal to the outdoor condition because the house was unoccupied. While in hybrid mode, the CO$_2$ level were lower ranging between 450 to 500 ppm demonstrating a better performance of the ground cooled air duct compared to other modes.

Some researchers found that the CO$_2$ level in the atmosphere during day time was much lower than night time (390 ppm and 425 ppm for day time and night time respectively) because those dormant photosynthesis cells is power-up during day time and they use CO$_2$ for that process (Chapman and Gleason, 1954, provide more citations since you claimed “some researchers found”). According to ASHRAE Standard 62.1-2004, CO$_2$ concentrations in outdoor air typically range from 400 to 500 ppm (ASHRAE62.1 2004) whereas the indoor CO$_2$ level is expected to be higher than outdoor due to human activities.

### 3.2 Absolute Humidity Measurements

Figure 6 shows that the outdoor absolute humidity levels were relatively stable averaging at 23 ± 1 g/m$^3$ air. The 24-hour air conditioned indoor environment of CoolTek house had a 35% lower humidity level than outdoor humidity at all times.

<figure>

![Figure 6: Average absolute humidity measurements (period A – F)](image)

The absolute humidity level in ground cooled air duct during fully passive mode seemed to be slightly higher during daytime than outdoor measurements; presumably because warm outdoor air absorbed water vapour from moist sub-soil concrete chambers. The absolute humidity measurements in passive mode showed a 32% decline compared to fully passive mode and nearly matched the indoor level during day time indicating that the origin of the air in the ground cooling system duct was from indoors. This further confirms that the air flow in ground cooled air duct was reversed at day time which support the observation for CO$_2$ measurements (section 3.2). The absolute humidity during hybrid mode was relatively stable throughout the day and followed the indoor humidity profile. This indicates that the mounted auxiliary fan assisted the solar chimney, so that fresh air
was pulled through the ground cooled air ducts in the day time at a speed that prevented the fresh air from condensing as well as avoiding the outdoor fresh air to become too moist.

3.3 Air Enthalpy Calculation

In order to investigate whether the ground cooling system of inlet air helps to increase the energy efficiency of the house during passive and hybrid modes, an air enthalpy calculation was carried out at 3pm at peak outdoor temperature (Table 3). The bedroom air presented the indoor air set point.

<table>
<thead>
<tr>
<th>Location/Mode</th>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Outdoor</td>
<td>33.8</td>
<td>63</td>
<td>88.2</td>
</tr>
<tr>
<td>B. Indoor (Bedroom)</td>
<td>26.8</td>
<td>56</td>
<td>58.6</td>
</tr>
<tr>
<td>E. Ground Cooled Air (Passive)</td>
<td>28.0</td>
<td>64</td>
<td>67.2</td>
</tr>
<tr>
<td>F. Ground Cooled Air (Hybrid)</td>
<td>28.2</td>
<td>77.5</td>
<td>76.4</td>
</tr>
</tbody>
</table>

As a result, the performance of the system during passive mode cannot be used for comparison with the performances of hybrid mode operation because it is based on a reversed air-flow, the cooling during passive mode is done by air-conditioning and not by the ground cooling. The origin of the air in the ground cooling system duct during passive mode came from indoors at day time which reversed flow and not through the ground cooling system. Reimann et al. (2007) proposed that this phenomenon was related to the thermal buoyancy force because the ‘thermal pull’ solely delivered by the solar chimney was not strong enough to counteract the reverse buoyancy effect delivered by the air-conditioned and ‘heavy’ air (24°C-26°C) that dropped out of the floor ventilation pipes and was replaced by warm and ‘light’ outdoor air temperature (30°C). Whereas, for Hybrid mode which is the ground cooled air experienced slight moist in the sub-soil chamber, but it can still reduce the outdoor air enthalpy slightly to 76.4 kJ/kg, or reduce 40% of cooling load.

4 Conclusion

The performance of the ground cooling system installed at CoolTek house showed that when the CoolTek house was in fully passive mode operation, the air in the ground air cooled duct flowed naturally into the house all the time. However, the measurements indicated that the ground cooling system adds moisture to the indoor air which will to some extent affect the use of energy during start-up of the air conditioning system to dehumidify the moist air as well as affect furniture and home appliances that are sensitive to high humidity levels.

When the CoolTek house was ventilated by solar chimney with 24 hours of air-conditioning, the air flow in the ground cooling system ducts was found to flow in the opposite direction at day time due to the thermal buoyancy effect. In contrast, when forced ventilation of the CoolTek house was deployed, the ground cooling system delivered an almost constant air temperature of 28°C all day. At peak temperature in the afternoon, the ground cooling system was able to reduce 40 % of the cooling load despite experiencing a slight increase in humidity.

In general, the ground cooling system has potential in hot and humid climate when forced ventilation in conjunction and shaded air intake from the daytime solar radiation with air-
conditioning is used in well-sealed buildings. A hybrid ventilation system allows the controlled introduction of outdoor air ventilation into a building by both mechanical and passive means and it was save electricity consumption at CoolTek house about 418 kWh/year – or RM137.89 in local currency compared to passive ventilation. Passive ventilation systems alone consisting of solar chimney and ground cooled air ducts, which has no way of controlling the amount of outdoor air load, was found to be unsuitable for CoolTek house and in general for buildings in tropical humid climates. Based on this study, further investigation should be done on indirect ventilation system by recirculating the indoor air in order to reduce the reception moist air directly from the ground cooling system ducts.

Acknowledgements
This study is fully sponsored by Majlis Amanah Rakyat (MARA) under full-time study leave scheme. The support from supervisors, MGEEB classmates batch 5, Nuriha Mohamed and family is highly appreciated.

References


DOES TROPICALLY ADAPTED COOLTEK HOUSE COMPLY WITH SELECTED PASSIVHAUS REQUIREMENTS?

Nur Azureen Binti Amernudin1,4, Stephanie Bacon2, Gregers Reimann3 & Robert Thomas Bachmann1

1 Malaysian Institute of Chemical and Bioengineering Technology, Universiti Kuala Lumpur, Lot 1988, 78000 Alor Gajah, Malaysia, zureenudin_life@yahoo.com and bachmann@unikl.edu.my
2 CoolTek, Malaysia, cooltek.my@gmail.com
3 IEN Consultant, Malaysia, gregers@ien.com.my
4 University of Applied Science Rosenheim, Hochschulstraße 1, 83024 Rosenheim, Germany

Abstract: Malaysia has a climate of uniformly high temperatures and humidity as well as abundant rainfall throughout the year. Buildings in Malaysia with high thermal mass therefore act like energy storage facilities which absorb heat thus keeping the building interior relatively cool during the day but release the heat at night causing thermal discomfort. According to government’s aspiration, Vision 2020, Malaysia will experience an increased demand in living space over the next few years. To maintain low to moderately priced living space residential affordable houses are not optimally designed in term of cooling load and energy consumption which contributes to global warming. To overcome this problem, various construction companies and individuals started to build energy efficient residential building that use less energy to provide same level of performance, comfort and convenience during use with lower operational cost. One innovative approach that has been well-documented is the CoolTek House concept built in 2005 in the state of Malacca, Malaysia. This one storey house has a gross floor area of 179 m², designed to reverse the role of the building envelope of colder climates from keeping the heat inside the building to keeping the heat and humidity out of the building. In order to assess the performance of energy efficient buildings such as CoolTek the Passivhaus Standard for Warm European Climate may be used due to its focus on dramatically reducing the requirement for space heating and cooling, whilst also creating desirable indoor comfort levels. The result showed that Passivhaus Standards were achieved only in terms of i) average primary energy (33.3 ± kWh/m²·yr). Other requirements exceeded the standard. It is recommended to further enhance the air tightness of the ceiling to reduce air leakage and thus cooling demand.

Keywords: energy consumption, energy efficient, measurement, performance, cooling load
1 Introduction

The most common type of home for Malaysians is terraced house. These houses have become the backbone of the housing industry in Malaysia and are favoured by the growing middle-income groups who find them affordable (Rilling et al., 2006). In order to maintain affordability, the houses are not designed to the optimum in terms of cooling load and energy consumption (Ismail et al., 2010). Thus to overcome this problem, some private companies have started to build energy efficient residential buildings. Energy efficient buildings use less energy to provide the same level of performance, comfort and convenience. The ideal energy efficient home maintains the best environment for living while reducing the cost of energy.

The CoolTek one-storey house with a gross floor area of 179 m$^2$ was built in 2005 within the boundaries of a golf and country club in the state of Melaka, Malaysia. (Figure 1). The owners deliberately choose to reside in Malaysia in order to make use of the constant and relatively predictable weather to easily control their expected indoor environment for thermal comfort. The house was designed taking into account orientation, protection, insulation and ventilation (Bacon, 2009).

The main air conditioned living room windows face North and South thereby preventing the direct sun radiation from entering and increasing room temperature. The shortest length of the wall faces East and West in order to restrict heat gain from morning and afternoon sun respectively. All windows and doors are double-glazed, low-e glass with argon gas to reduce heat transfer to the building interior. The walls are built with lightweight aerated concrete blocks and painted with white colour to reflect the heat. The roof is made from zinc aluminium coated steel and white colour, with wide overhangs to add extra shading to every window and wall. A 50mm layer of Rockwool insulation was laid on top the ceiling to prevent the air-conditioned air below to absorb heat from the roof void.

There are two ventilations for the house: split air-conditioners and air supply system. There are four spilt units with R410A hydro chlorofluorocarbon (HFC) refrigerant. The supply system comprised a dark colour solar chimney built with red bricks to absorb heat in order to create sufficient pressure differences for allowing a “stack effect” to draw spent and warm air out of the house to be replaced with fresh and filtered air through an underground supply chamber. The underground chamber was built using a PC drum with clay pipes inside it to absorb heat from inlet and then buried into the slope beside the house in a well shaded area. Plus, most of the electrical equipment is energy efficient rated. CoolTek House was named the winner of the ASEAN Energy Award for 2009.
An energy audit was conducted on the CoolTek house from 2 to 31 July 2008 (ASEAN Energy Awards, 2008). CoolTek House uses about 63% less electricity than the typical house(Table1). Energy efficient design features and energy efficient electrical appliances helped to reduce electricity consumption in CoolTek House.

Table 1: Comparison of electrical energy consumption

<table>
<thead>
<tr>
<th></th>
<th>Comparative house</th>
<th>CoolTek house</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily consumption (kWh)</td>
<td>13.94</td>
<td>8</td>
</tr>
<tr>
<td>No of days</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Annual consumption (kWh)</td>
<td>4,879</td>
<td>2,843</td>
</tr>
<tr>
<td>Ground floor area m²</td>
<td>148</td>
<td>232</td>
</tr>
<tr>
<td>Energy index (kWh/m²/yr)</td>
<td>2.75</td>
<td>1.02</td>
</tr>
<tr>
<td>Comparison result</td>
<td></td>
<td>37%</td>
</tr>
</tbody>
</table>

The term ‘Passivhaus’ refers to a low-energy construction standard developed in the 1990s by the Passivhaus Institute in Germany (Zangheri et al., 2009). Core focus of the Passivhaus standard is to dramatically reduce the requirement for space heating and cooling, whilst also creating excellent indoor comfort levels. The basic Passivhaus principles for warm European climate are that i) the useful, sensible energy need for space cooling should not exceed 15 kWh per m² net habitable floor area per annum, ii) the primary energy demand for all energy services, including heating, domestic hot water, auxiliary and household electricity does not exceed 120 kWh per m² net habitable floor area per annum, iii) good indoor air quality and high thermal comfort are achieved by means of a mechanical ventilation system, and iv) the building envelope should pass a pressurization test (50 Pa) according to EN 13829 of no more than 0.6 h⁻¹. The comfort criterion is defined in EN 15251 and, in case of the use of an active cooling system as the major cooling device; the operative room temperature can be kept below 26°C.

The objectives of this research were therefore to obtain weather data between Melaka, Malaysia and several cities in Southern Europe to establish whether Melaka climate is comparable to warm European climate, as well as to determine whether the CoolTek House concept complies with the Passivhaus Standard for Warm European Climate based on primary energy consumption, cooling profile, air tightness and thermal comfort.

2 Methodology

The energy efficiency of the Cooltek House was evaluated based on criteria from Passivhaus Standard for Warm European Climate.
2.1 Weather and Location
Melaka weather data were collected using a Davis Wireless Weather Station operated 24 hours per day. The wireless station was mounted on top of the store room roof. ‘Davis’ monitored indoor and outdoor temperature, wind speed, wind direction, precipitation and humidity. Data were transferred from the station to a PC and downloaded in table form for analysis. Europe weather data were collected online from ‘The Weather Channel’. Data collected everyday for cities from five countries were:

1. Athens, Greece
2. Barcelona, Spain
3. Lisbon, Portugal
4. Marseille, France
5. Rome, Italy

2.2 Energy Consumption
The latest energy consumption of the Cooltek House was determined for single occupancy. Owing to a busy daily schedule of the owner, the number of days the house was occupied in a month varied. In order to monitor the current energy consumption and cooling energy demand of the house, plug-in energy meters(Power Meter UT230B) were used for electrical appliances such as refrigerator, personal computer and television. Data were collected once a month for August, September and October 2016, and analysed using a spreadsheet. Typical operational hours of electrical appliances are summarised in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Appliance</th>
<th>Operational Hours [hr/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cooling demand</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Refrigerator</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>Lighting</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Microwave</td>
<td>18 min per use</td>
</tr>
<tr>
<td>5</td>
<td>Kettle</td>
<td>3x per day</td>
</tr>
<tr>
<td>6</td>
<td>Dishwasher</td>
<td>3x per week</td>
</tr>
<tr>
<td>7</td>
<td>Washer machine</td>
<td>3x per week</td>
</tr>
<tr>
<td>8</td>
<td>Personal computer</td>
<td>variable</td>
</tr>
<tr>
<td>9</td>
<td>Television</td>
<td>variable</td>
</tr>
</tbody>
</table>

2.3 Cooling Creation
The cooling demand of CoolTek was determined by monitoring the electricity consumption of the split air conditioning units (set point 24°C) while all other electrical appliances including refrigerator were turned off. Electricity consumption readings were obtained from the energy meter (Malaysian Intelligence Meters) installed at CoolTek by electrical power supplier Tenaga Nasional Berhad (TNB).

2.4 Primary Energy
Total primary energy requirement is a measure of all of the energy consumed by the organization and accounts for the energy that is consumed and/or lost beyond the boundary of the organization – in energy transformation, transmission and distribution processes, e.g. electricity generation transmission and distribution. Energy mix in Malaysia is contributed by five main sources namely natural gas, coal, oil, hydro, and
renewable energy. Among the fossil fuels resources for energy generation, coal is the major consumption. The consumption of coal in Malaysia is growing at the rate of 9.7% per year since 2002(Jamaludin, A., 2009). Basically, oil, coal, gas and hydropower are the raw materials for electricity generation(AI-Amin et al., 2009). To calculate primary energy for CoolTek, conversion efficiency and transmission losses needed(International Energy Agency., 2014). The primary energy for electricity plant as showed in table 3.

Table 3: Primary energy

<table>
<thead>
<tr>
<th>No.</th>
<th>Kind of primary energy</th>
<th>(k toe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coal</td>
<td>13,648</td>
</tr>
<tr>
<td>2</td>
<td>Oil product</td>
<td>916</td>
</tr>
<tr>
<td>3</td>
<td>Natural gas</td>
<td>17,552</td>
</tr>
<tr>
<td>4</td>
<td>Hydro</td>
<td>1,151</td>
</tr>
<tr>
<td>5</td>
<td>Geothermal</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>Bio fuels</td>
<td>241</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>33,528</td>
</tr>
<tr>
<td></td>
<td>Total Electricity used</td>
<td>12,682</td>
</tr>
<tr>
<td></td>
<td>Wasted</td>
<td>20,846</td>
</tr>
</tbody>
</table>

Table 4: CoolTek electric energy used each month

<table>
<thead>
<tr>
<th>No.</th>
<th>Month</th>
<th>Energy used (kWh/ m² yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August</td>
<td>24.74</td>
</tr>
<tr>
<td>2</td>
<td>September</td>
<td>20.25</td>
</tr>
<tr>
<td>3</td>
<td>October</td>
<td>25.34</td>
</tr>
</tbody>
</table>

2.5 **Air Tightness**

Unwanted air leakage significantly increases the space cooling demand of a building. In order to reduce cooling demand, the building must have good air tightness level. According to the owner, Cooltek house was declared as an airtight house due to the use of sealed windows and doors. The pressurisation test was carried out in accordance with the Blower Door Test (ASTM E779-03). In brief, the procedure was as follows:

1. All interconnecting door of the airtight building component were opened. All doors and windows were closed.
2. Operable dampers were closed.
3. General observations of the condition of the building, the doors, windows, opaque walls, roof and floor were noted.
4. Measure and record indoor and outdoor temperature at the beginning and the end of the test to compute their average value. If the product of the absolute value of the indoor/outdoor air temperature difference multiplied by the building height, give a result greater than 200 mºC, do not perform the test, because the pressure difference induced by the stack effect is too large to allow accurate interpretation of the result.
5. Measure wind speed using Davis weather monitoring station (section 2.1). Preferred test conditions are wind speed of 0 to 2m/s and outside temperature from 5ºC to 35ºC.
6. Blower door assembly was connected to the building envelope using vent opening from ground cooling system. Openings were sealed to avoid leakage at these points.
7. Install the pressure measuring device across building envelope.
8. Measure zero flow pressure with the fan opening blocked. These zero flow envelope pressure is measured before and after the flow measurement. These zero flow pressures are to be subtracted from the envelope pressures measured during pressurization and depressurization.
9. The range of the induced pressure difference shall be from 10 to 60 Pa. use increment of 5 to 10 Pa for the full range of induced pressure differences.
10. At each pressure difference, measure the airflow rate and the pressure differences across the envelope. After the fan and instrument have stabilized the average over at least a 10-s interval should be used.
11. For each test, collect data for both pressurization and depressurization.

For this study, there’s no fan that mount in a building envelope (blower door test) to pressurize the building. Fan with power 520watt and 300mm diameter was mounting at ground cooling hole located outside the house. All interior doors are opened, and all exterior doors and windows are closed. All electrical appliances were shut down during the testing. Inside and outside temperature were taken beginning and at the end of the testing. Wind speed also was record before testing start. No manometer was use in this testing. A two meter transparent rubber tube was used. The tube was place at a door. One end of the tube was located outside and another was inside the building. Water was pour into the tube that located inside the testing area. One person was standby in the house to monitor and record the height water difference in the tube. The fan turn on and start to blow until the pressure difference between the indoors and the outdoors reaches 50 Pascal. The fan starts to blow air at 12:40pm and end at 1:30pm. The testing takes 50 minutes. The height differences between two pints of water level in the tube will record with 5 minutes interval. Table 5 showed the result.

<table>
<thead>
<tr>
<th>No.</th>
<th>Time (minute)</th>
<th>Δ Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>-0.1</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>-0.1</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>-0.5</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>
2.6 Thermal Comfort
Comfort criterion room temperature summer: in warm and hot seasons, operative room temperature remains within the comfort range defined in EN 15251. If an active cooling system is the major cooling devices, the operative room temperature can be kept below 26°C. CoolTek House use active cooling system as major cooling devices. Air-conditioning in the house was running 24 hours. Owner set the operative temperature to 24°C all the time.

3 Results and Discussion
3.1 Weather and Location
Figure 4 compares the average temperature in Melaka, Malaysia with various cities in southern Europe for August, September and October for 2016. It can be seen that Melaka got the highest temperature for all three months, followed by Athens, Lisbon, Rome, Marseille and Barcelona. The drop in temperature for European cities illustrate that they are still subject to seasonal effects in contrast to Melaka which experiences only minor variations as expected. This situation was effect the building performance. When temperature rises, building will store more heat and need more energy to reduce the heat and maintain set point temperature. Seasonal changes also may affect the building performance. During August to October, its summer changes to autumn season. During summer season, temperature were high need more energy to keep building
comfort while during autumn, temperature decrease and need less energy to cooling down the building but need more energy to heat the building in order to maintain thermal comfort of the building.

![Figure 4: Average temperature in Melaka, Malaysia and selected cities in southern Europe in 2016](image)

![Figure 5: Average Humidity in Melaka, Malaysia and Southern Europe in 2016](image)

The relative humidity in European cities and Melaka is depicted in Figure 5. Athens has the lowest humidity for all three months probably due to its more continental location away from large water bodies and prevailing wind direction from East. In October, almost all cities experience increased humidity due to lower temperatures which reduces the ability of air to absorb moisture. High humidity with low temperature might cause fungal on materials and will make people feel chilled.
Figure 6: Average Precipitation in Malaysia and Southern Europe in 2016

The Malaysian state of Melaka experiences the highest precipitation for all three months whereas most Southern European cities with exception of Athens receive increasing as the seasons progresses towards autumn. High precipitation may decrease the temperature and then reduce cooling energy but will increase the humidity and may affect the building materials and occupant thermal comfort.

3.2 CoolTek House

3.2.1 Energy Consumption
The electricity energy consumption in Cooltek House during August to October was monitored and summarised in Table 6.

<table>
<thead>
<tr>
<th>Month</th>
<th>House Occupation (days)</th>
<th>Energy (kWh)</th>
<th>Charge (RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>15</td>
<td>369</td>
<td>111</td>
</tr>
<tr>
<td>September</td>
<td>16</td>
<td>302</td>
<td>74.80</td>
</tr>
<tr>
<td>October</td>
<td>20</td>
<td>378</td>
<td>116</td>
</tr>
</tbody>
</table>
As demonstrated in Figure 7, the highest electricity consumption is the cooling demand, 78% (273 kWh) followed by refrigerator, 13% (45.06kWh). These results confirm previous energy audits carried out for CoolTek house (Asean Energy Awards, 2008). The average monthly electricity consumption for the CoolTek house was found to be 348 ± x kWh which exceeds the national monthly average of 251 kWh / month. However, the national average value comprises of mechanically ventilated as well as air conditioned domestic buildings. The average monthly electricity consumption for the
CoolTek house was found to be 348 kWh which exceeds the national monthly average of 251 kWh/month. However, the national average value comprises of mechanically ventilated as well as air conditioned domestic buildings.

Figure 9: CoolTek yearly energy consumption

Figure 9 show energy consumption sort by electrical appliance of CoolTek house. The cooling demand consumes the largest amount of energy (3281 kWh) followed by refrigerator (541 kWh). Both electrical appliances are 24 hours operation. Others electrical appliances are consume with certain period. Figure 10 show energy consumption by residential in Malaysia. Cooling demand is the highest consumption (1167 kWh) followed by refrigerator(597 kWh). Others appliance energy consumption quite high compares to CoolTek house because of energy star appliance that owner of CoolTek house use. For cooling demand in residential Malaysia, average operation hours are 6 to 8 hours per day, where occupant frequently consumes cooling energy during night time.

Figure 10: Residential in Malaysia yearly energy consumption
3.3 Passivhaus Standard

3.3.1 Cooling creation

The absolute and specific cooling demand for Cooltek House for three months is summarized in Table 7. CoolTek gross area is 232m² and conditioned area is 179m². Drop in cooling demand in September due to low outdoor temperature and split unit were off for 10 days. The lowest temperature is 27.5°C and only two days was high which is 29.5°C and less occupancy.

Table 7: Absolute and specific cooling demand of CoolTek House

<table>
<thead>
<tr>
<th>Month</th>
<th>Cooling Demand (kWh)</th>
<th>Cooling Creation (kWh/m². yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>297.45</td>
<td>19.94</td>
</tr>
<tr>
<td>September</td>
<td>230.12</td>
<td>15.43</td>
</tr>
<tr>
<td>October</td>
<td>292.60</td>
<td>19.62</td>
</tr>
</tbody>
</table>

Comparing the average cooling demand, of CoolTek House (18.33 kWh / [m² yr]) with the Passivhaus Standard 15kWh/[m² yr] it can be conclude that CoolTek house cooling demand exceed Passivhaus standard. It should noted that the cooling demand may increase/decrease depends on the number of occupancy. Typical residential in Malaysia air conditioner daily usage hour was 6 hours on average (Kubota et al., 2011). For CoolTek, daily usage hour was 24 hours.

3.3.2 Primary energy

August primary energy

\[
(\text{Energy losses}) = \text{Energy used} \times (\text{conversion efficiency} + \text{transmission losses})
\]

\[
24.74 \frac{kWh}{m². yr} \times (38\% + 4.04\%) = 10.40 \frac{kWh}{m². yr}
\]

\[
\text{Energy used} + (\text{Energy losses}) =
\]

\[
24.74 \frac{kWh}{m². yr} + 10.40 \frac{kWh}{m². yr} = 35.14 \frac{kWh}{m². yr}
\]

Table 8: CoolTek primary energy demand

<table>
<thead>
<tr>
<th>No.</th>
<th>Month</th>
<th>Primary energy demand (kWh/m².yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August</td>
<td>35.14</td>
</tr>
<tr>
<td>2</td>
<td>September</td>
<td>28.76</td>
</tr>
<tr>
<td>3</td>
<td>October</td>
<td>36.00</td>
</tr>
</tbody>
</table>

The average Cooltek primary energy demand is 33.3 kWh/m².yr. Average Cooltek primary energy not exceed Passivhaus standard requirement (120kWh/m².yr). In order to achieve
primary energy target highly efficient appliances and equipment were needed. CoolTek has efficient appliance such as energy star split unit, refrigerator and washer machine.

3.3.3 Air Tightness
The air tightness test revealed an air change (ACH) of 1.67 h\(^{-1}\) while the required pressure difference of 50 Pa (EN 13829) could not be achieved. Inspection of the rooms suggests that the ceiling comprising of panels with 15 mm gaps may be the reason for air leakage, and lack of equipment showed that the air tightness test for reference pressure was fail. A study of 10 building in Malaysia, found that the measured total fresh ACH were as high as 2.0 ACH, with an average of 1.0 ACH per building (JKR, 2008). The Cooltek House ACH appears to be almost three times greater than Passivhaus Standard criteria and more than an average for building in Malaysia suggesting that further improvements in cooling demand reduction are possible.

3.3.4 Thermal Comfort
CoolTek House major cooling device is active cooling system and the operative temperature of room always set below 26\(^{\circ}\)C which is 24\(^{\circ}\)C. Figure 11 showed the average indoor temperature had exceeds 24\(^{\circ}\)C. Average indoor temperature is from 27\(^{\circ}\)C to 27.8\(^{\circ}\)C. This means the set point temperature not succeed to maintain low temperature as owner wanted.

![Figure 11: Average CoolTek indoor temperature(three months)](image)

4 Conclusion
Table 9 showed that only primary energy demand meet the Passivhaus Standard requirement. For cooling creation, air tightness and comfort creation, all exceed Passivhaus Standard requirement. Passivhaus has low ACH that CoolTek can't achieve. CoolTek house ACH also more than average standard for building in Malaysia. Air tightness is important for building to maintain comfort level and to reduce wasted cooling energy. Cooltek cooling creation is exceed Passivhaus Standard because of indoor temperature is high so need more cooling energy to reduce the heat.
Table 9: Conclusion of Passivhaus Standard and CoolTek

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Passivhaus Standard</th>
<th>CoolTek House</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling Creation</strong></td>
<td></td>
<td></td>
<td><strong>Exceed Standard.</strong> Average Cooltek cooling demand is 18.83 kWh/m².yr. However, more data required take into consideration effects of seasonal changes.</td>
</tr>
</tbody>
</table>
| (kWh/m². yr)              |                     |               | August : 19.94  
September : 15.43  
October : 19.62                                                                                                                                                                                              |
| **Primary Energy Demand** |                     |               | **Achieve Standard.** Each month value is less 3 to 4 times than Passivhaus Standard due to energy star electrical appliance.                                                                                                                                           |
| (kWh/m². yr)              |                     |               | August : 35.14  
September : 28.76  
October : 36.00                                                                                                                                                                                              |
| **Air tightness**         | Building envelope should have a pressurization test (50Pa) of no more than 0.6 ach⁻¹ | 1.67 h⁻¹       | **ACH CoolTek exceeds Passivhaus Standard.** Pressure differences not achieved because got air leakage from the ceiling comprising of panel.                                                                                                                                  |
|                           |                     |               |                                                                                                                                                                                                                                                                 |
| **Comfort Creation**      |                     |               | **Exceed Passivhaus Standard requirement.** The set point temperature fails to maintain indoor temperature below 26°C.                                                                                                                                            |
|                           |                     | Indoor temperature exceed 26°C |                                                                                                                                                                                                                                                                 |

References


